NOvA and MINOS

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University of Minnesota

The MINOS Collaboration

Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas
Fermilab • Harvard • IIT • Indiana • Minnesota-Duluth • Minnesota-Twin Cities
Oxford • Pittsburgh • Rutherford • Sao Paulo • South Carolina • Stanford
Sussex • Texas A&M • Texas-Austin •
Tufts • UCL • Warsaw • William & Mary

NOvA Collaboration

ANL / Athens / Banaras Hindu University/ Caltech / Cincinnati /Institute of Physics ASCR / Charles University / Cochin University / University of Delhi / FNAL / IIT Guwahati/ Harvard / University of Hyderabad/ IIT Hyderabad / Indiana / Iowa State / University of Jammu/ Lebedev / Michigan State/ Minnesota, Crookston / Minnesota, Duluth / Minnesota, Twin Cities / INR Moscow / Panjab University/ Sussex / South Carolina SMU / Stanford / Tennessee / Texas, Austin / Tufts / Virginia / WSU / William & Mary


Lake Nipigon
NOvA Far Detector
MINOS Far Detector
Minnesota
810 km
735 km
Green Bay
Georgian Bay
Lake Huron
Michigan
Wisconsin
Lake Michigan
Lake Erie
Fermilab
Fermilab
Iowa
Illinois
Indiana
Ohio
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Illinois
Indiana
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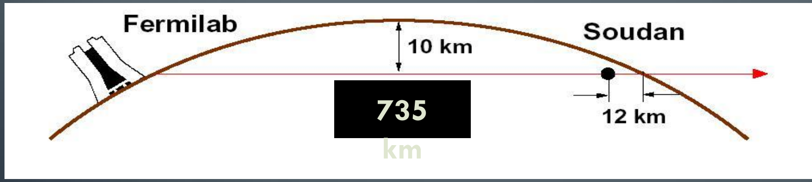
Pennsylvania
California
Kentucky
Virginia
Oklahoma
Tennessee
North Carolina
Arizona
New Mexico
Arkansas
South Carolina
Alabama
Georgia
Mississippi
Texas
Louisiana
Florida
Alaska
Hawaii
New Hampshire
Vermont
Massachusetts
Maine
Rhode Island
Connecticut
New Jersey
Delaware
Maryland
West Virginia

MINOS NOvA

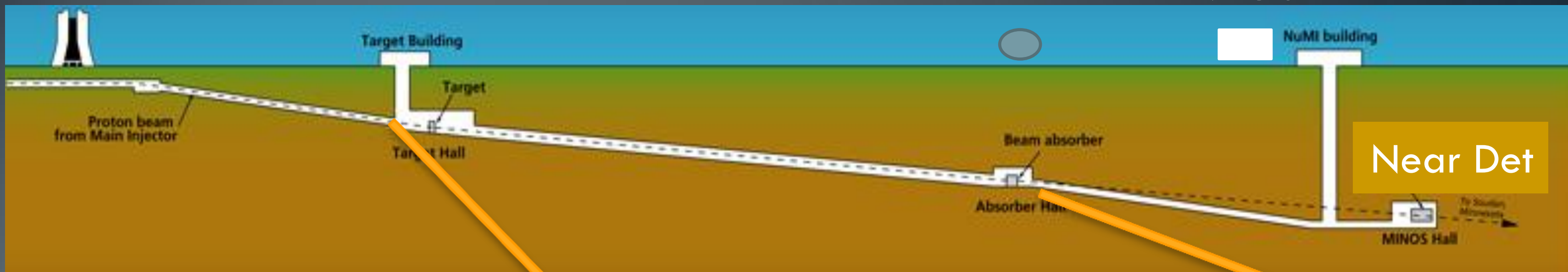
- A long-baseline neutrino oscillation experiment
- Near Detector at Fermilab to measure the beam composition 1km from source and 0.98kton
- Far Detector deep underground in the Soudan Underground Lab, Minnesota, to search for evidence of oscillations
- functionally identical to Near detector
- 735 km from source

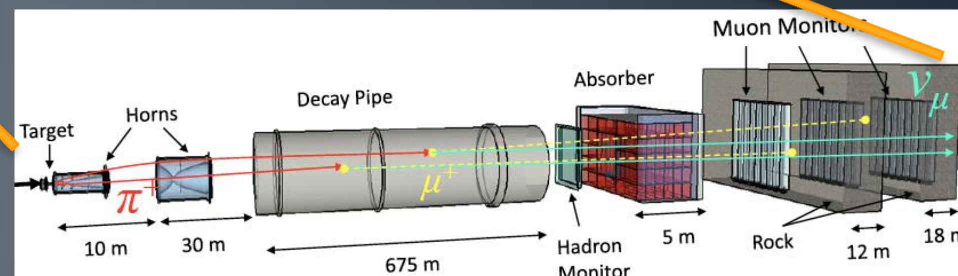


- Use the upgraded NuMI beam at Fermilab.
- Construct a totally active liquid scintillator detector off the main axis of the beam.
  - Far detector is 14 mrad off- axis and on the surface (14kton).
  - Near detector is also 14 mrad off-axis but underground(330ton).
  - Location reduces background.
- If neutrinos oscillate, electron neutrinos are observed at the Far Detector in Ash River, 810 km away.

NuMI beamline (Neutrinos at the Main Injector)

MiniBooNE NDOS

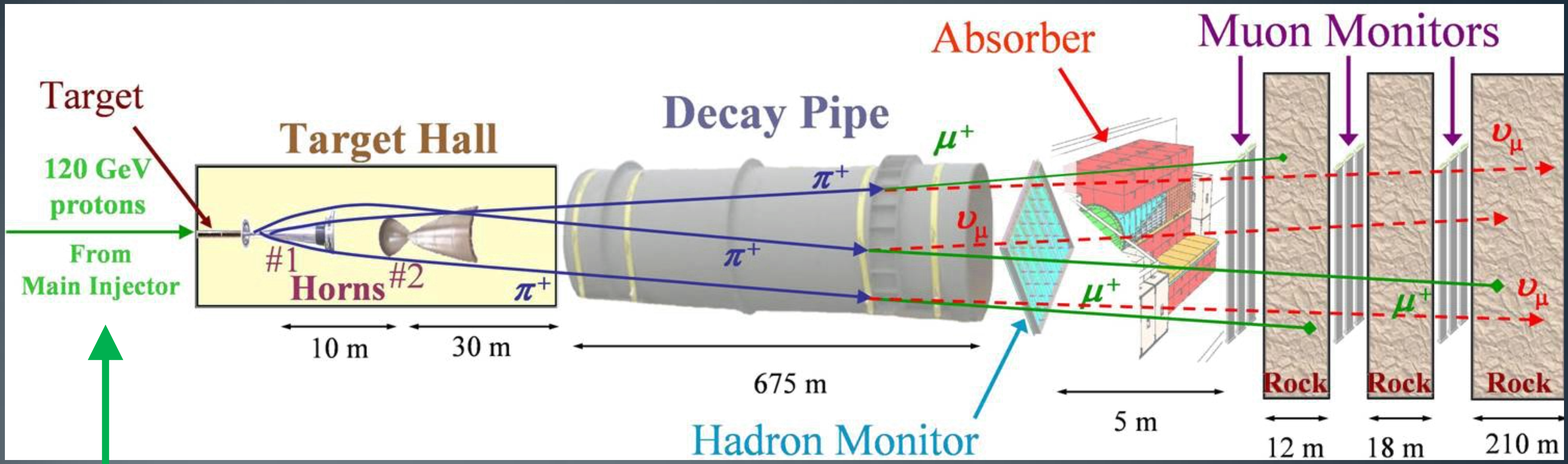




Cycle length is 2.2s
Typical peak NuMI beam power ~330 kW in mixed mode

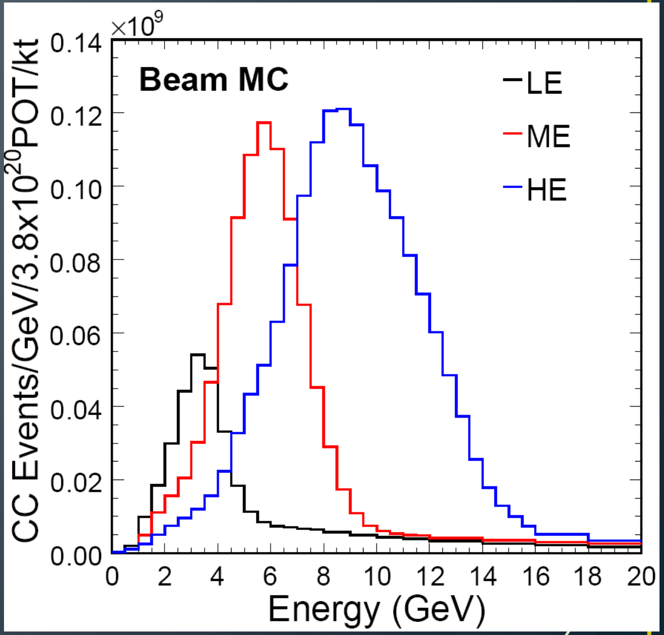
Linac: 750 keV – 400 MeV
Booster: 400 MeV – 8 GeV
Main Injector: 8 GeV – 120 GeV
Slip-stack 11 booster batches
2 batches to antiproton source
9 batches to NuMI

Neutrino Production with NuMI
(Neutrinos at the Main Injector)

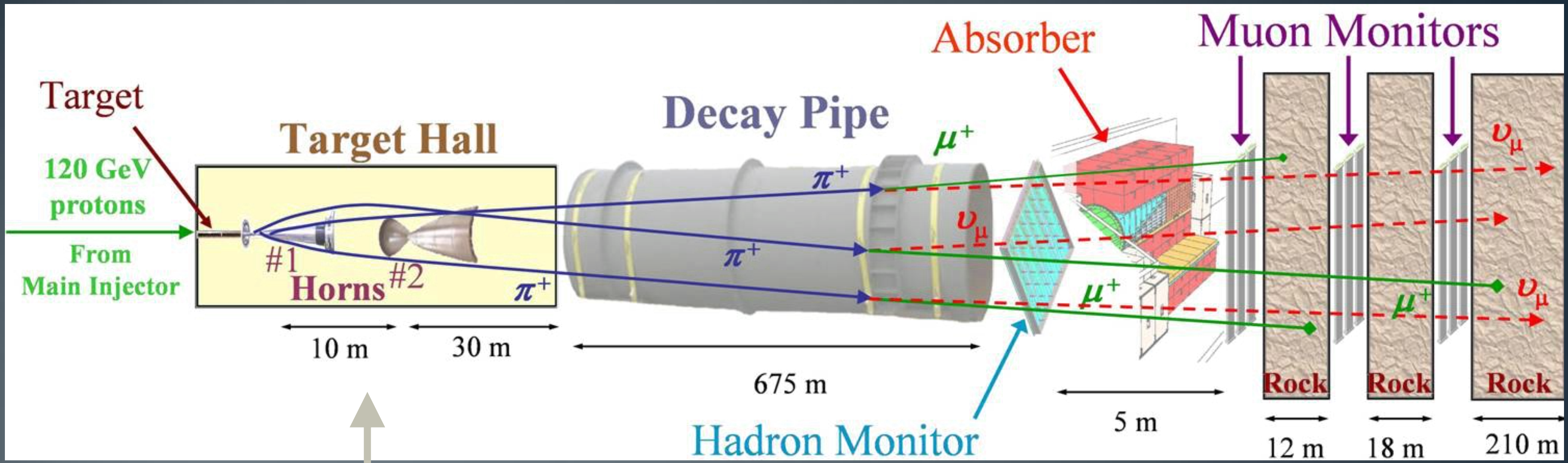


The Beam

- 120 GeV protons from the Main Injector
- ~330 kW beam power
- 10 μs spill of 120 GeV protons every 2.2 s
- 3.6×10^{13} protons per pulse
- Neutrino spectrum changes with target position



Neutrino Production with NuMI
(Neutrinos at the Main Injector)

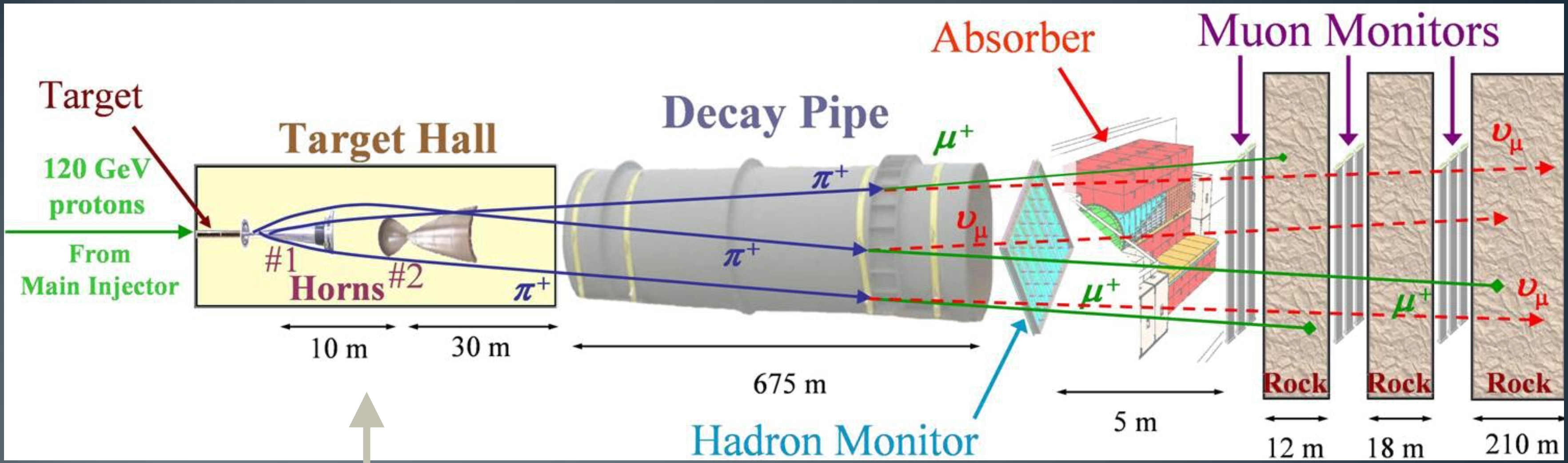


The Target and Production

- Protons strike a graphite target
  - 47 segments, 6.4 x15 x 20mm^3(MINOS)
  - ~95.4 cm long or 1.9 interaction length

Neutrino Production with NuMI

(Neutrinos at the Main Injector)

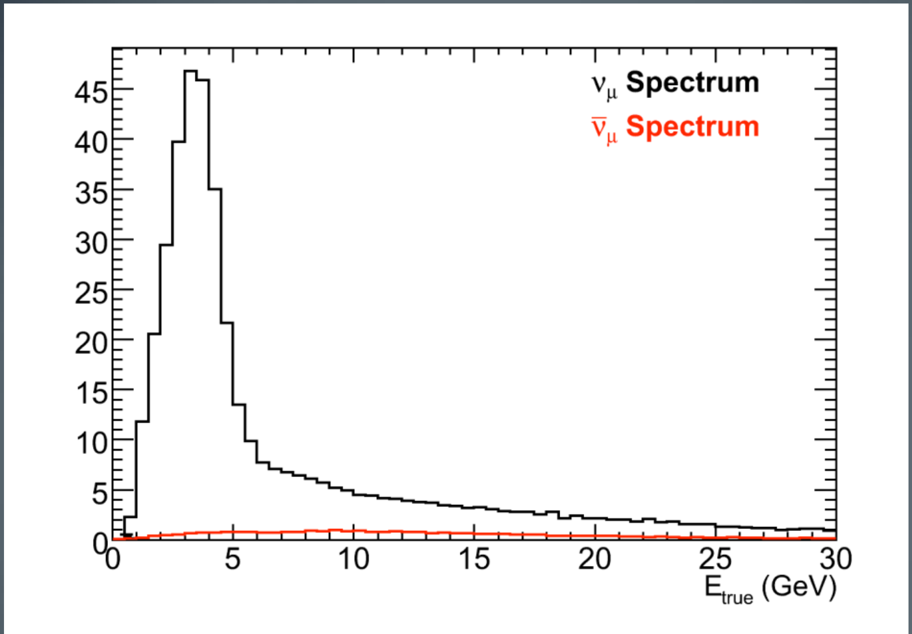


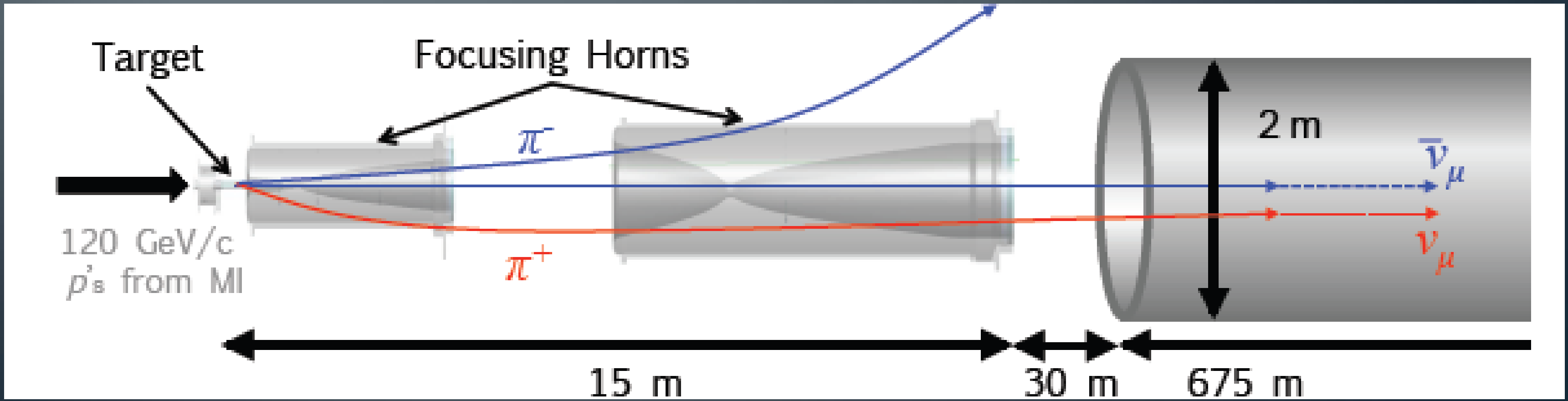
The Target and Production

- Protons strike a graphite target
  - 47 segments, 6.4 x15 x 20mm^3(MINOS)
  - ~95.4 cm long or 1.9 interaction length
- Two magnetic focussing horns guide mesons, mostly πs + Ks, down decay pipe
  - Pulsed horn current ~200kA
  - 3T magnetic field

Neutrino beam (FHC)

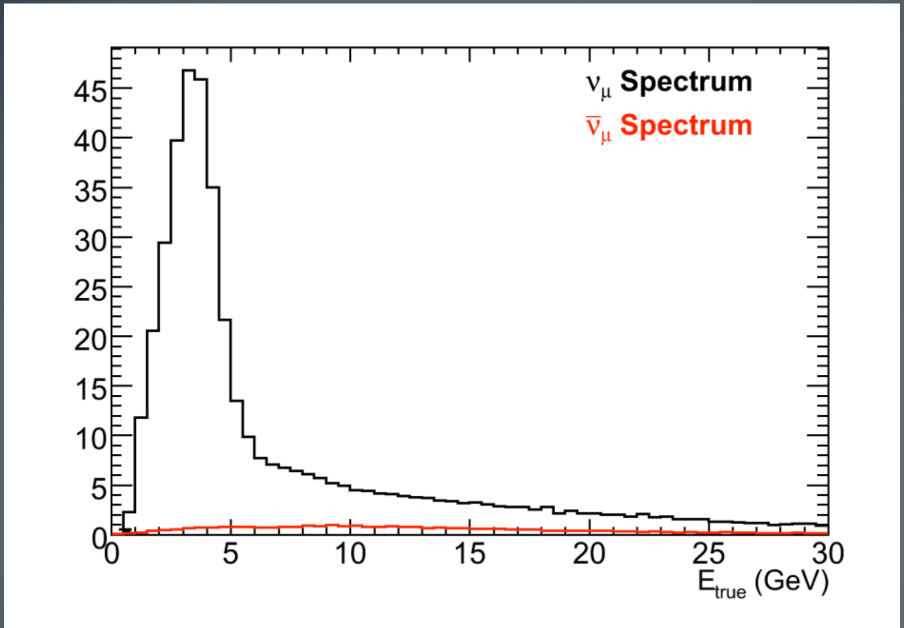
$$91.7\%\,\nu_\mu,\ 7.0\%\,\overline{\nu_\mu},\ 1.3\%\left(\nu_e+\overline{\nu_e}\right)$$





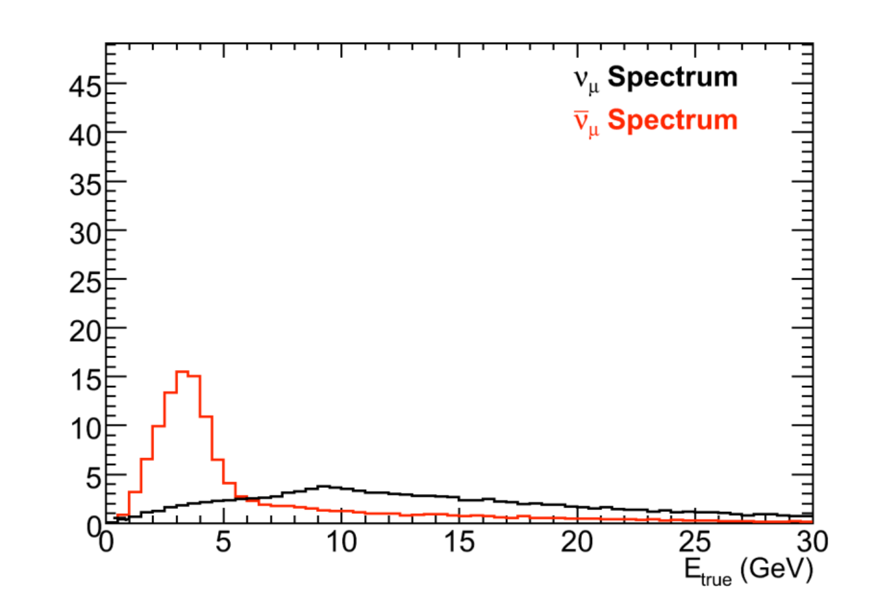
Neutrino beam (FHC)

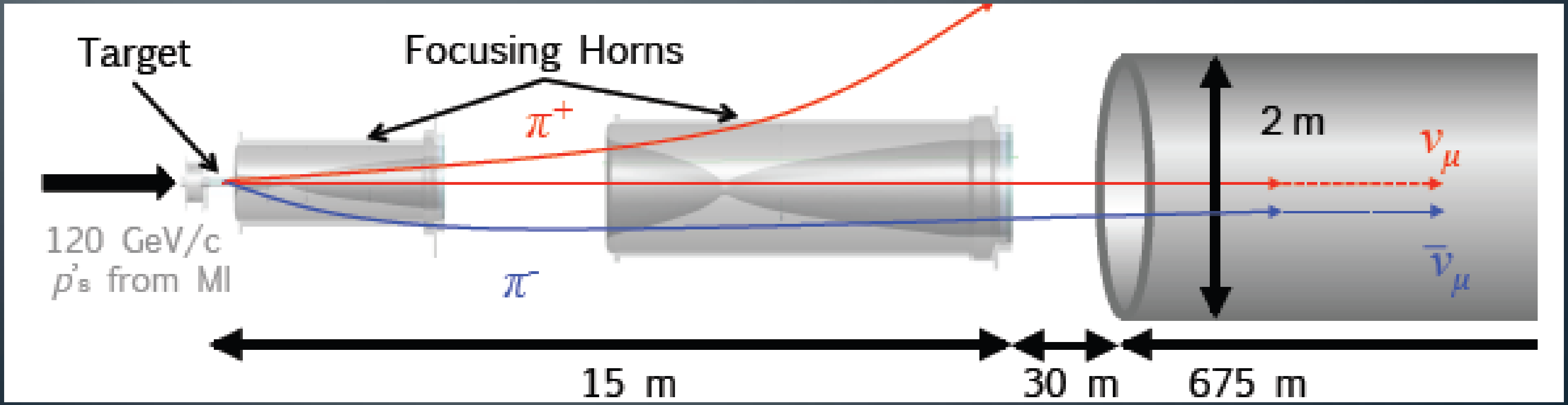
$$91.7\%\,\nu_\mu, 7.0\%\,\overline{\nu_\mu}, 1.3\%\left(\nu_e+\overline{\nu_e}\right)$$



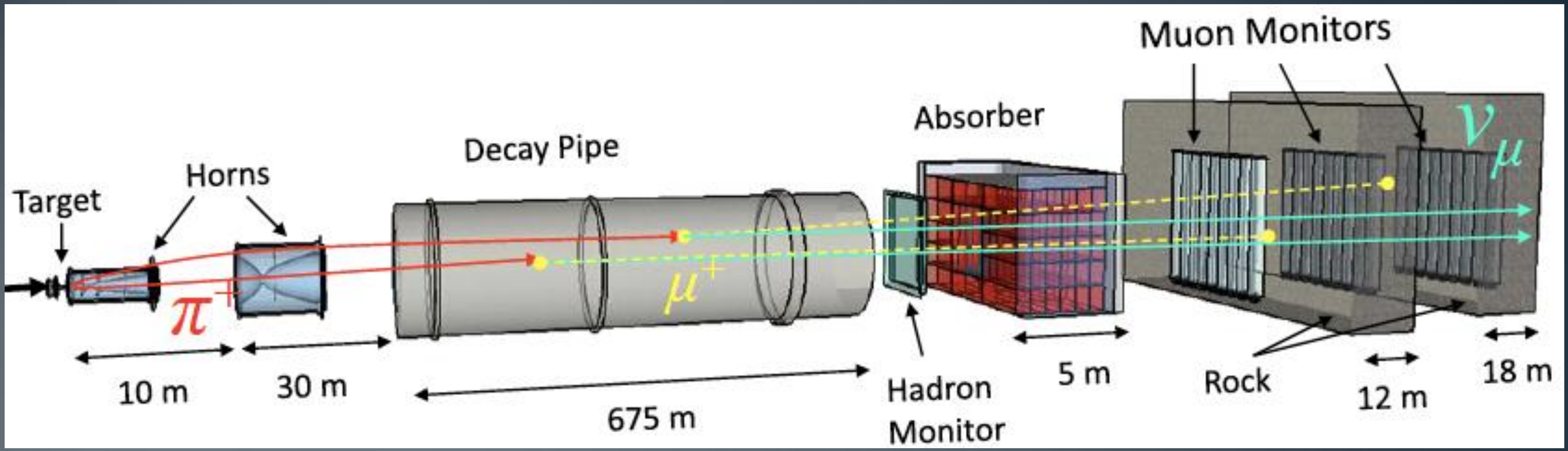
Anti-neutrino beam (RHC)

$$39.9\%\,\overline{\nu_\mu}, 58.1\%\,\nu_\mu, 2.0\%\left(\nu_e+\overline{\nu_e}\right)$$



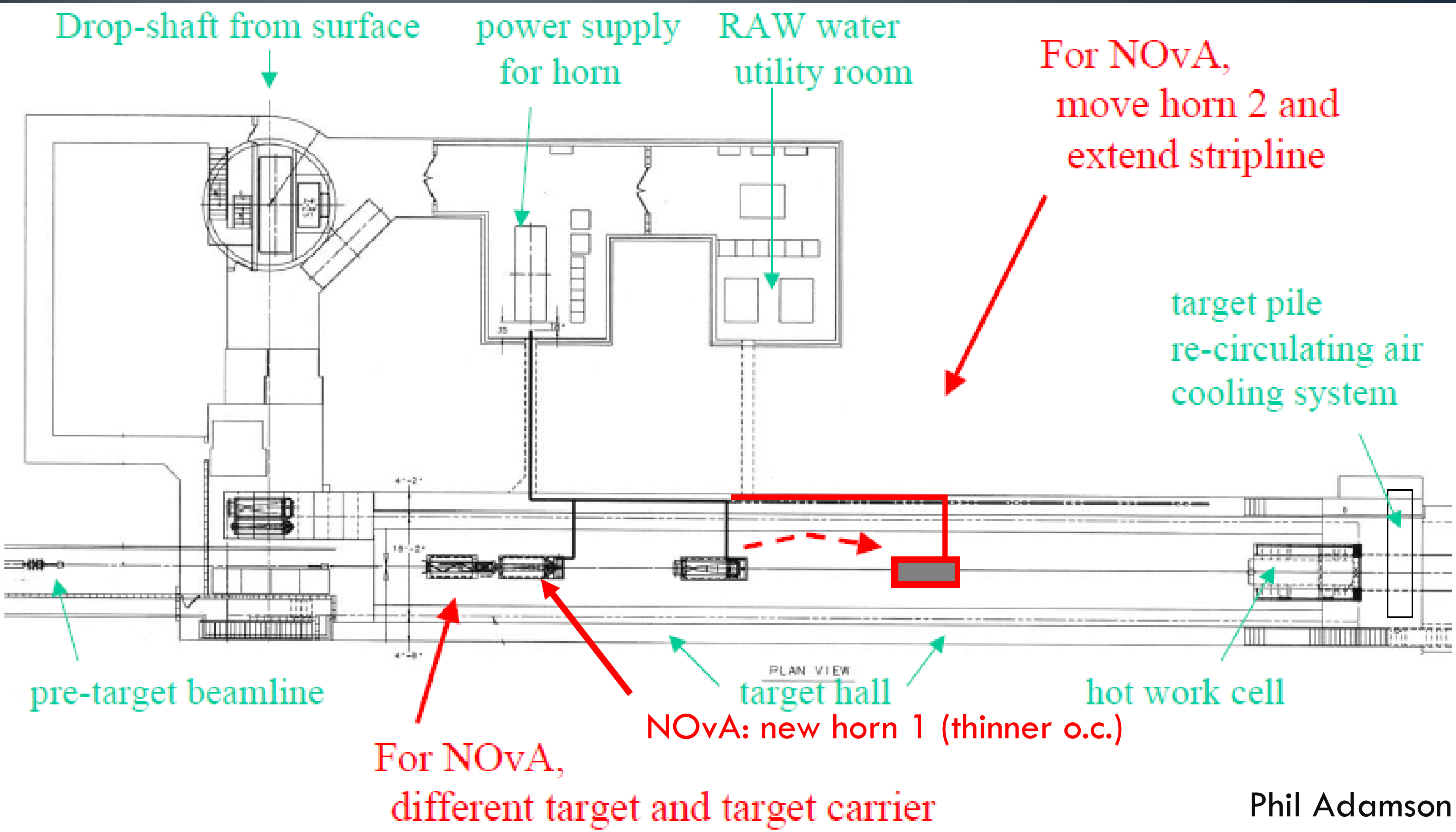


NuMI beam upgrade for NOvA experiment

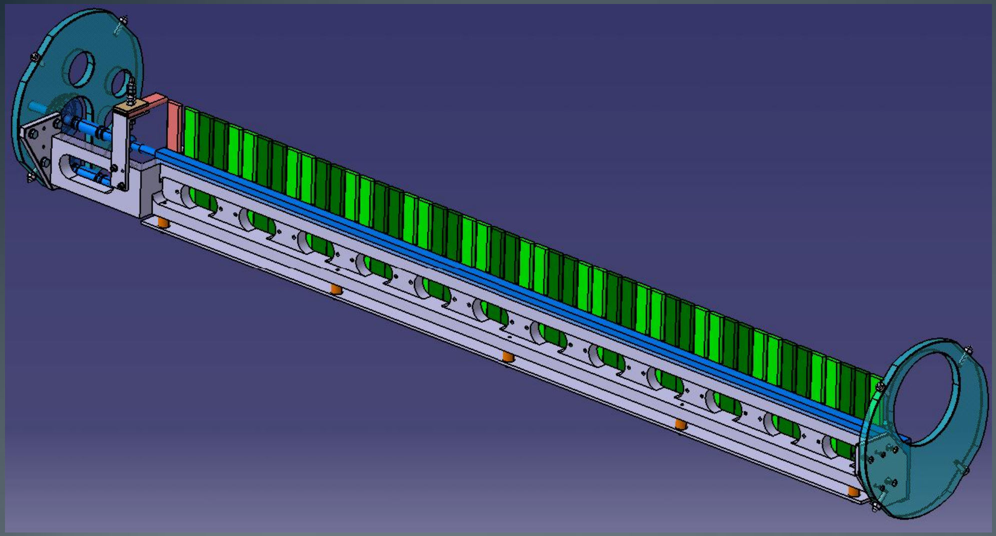


- Enhanced 700 kW NuMI beamline
- Reduce cycle time from 2.2 to 1.3 seconds.
- **Turn Recycler from antiproton to proton ring** *injection & extraction lines, associated kickers & instrumentation, 53 MHz RF*
- Increased intensity/cycle.
- New horn and target.
- 10μs beam pulse
- **4.9e13 POT/pulse or 6e20 POT/year**

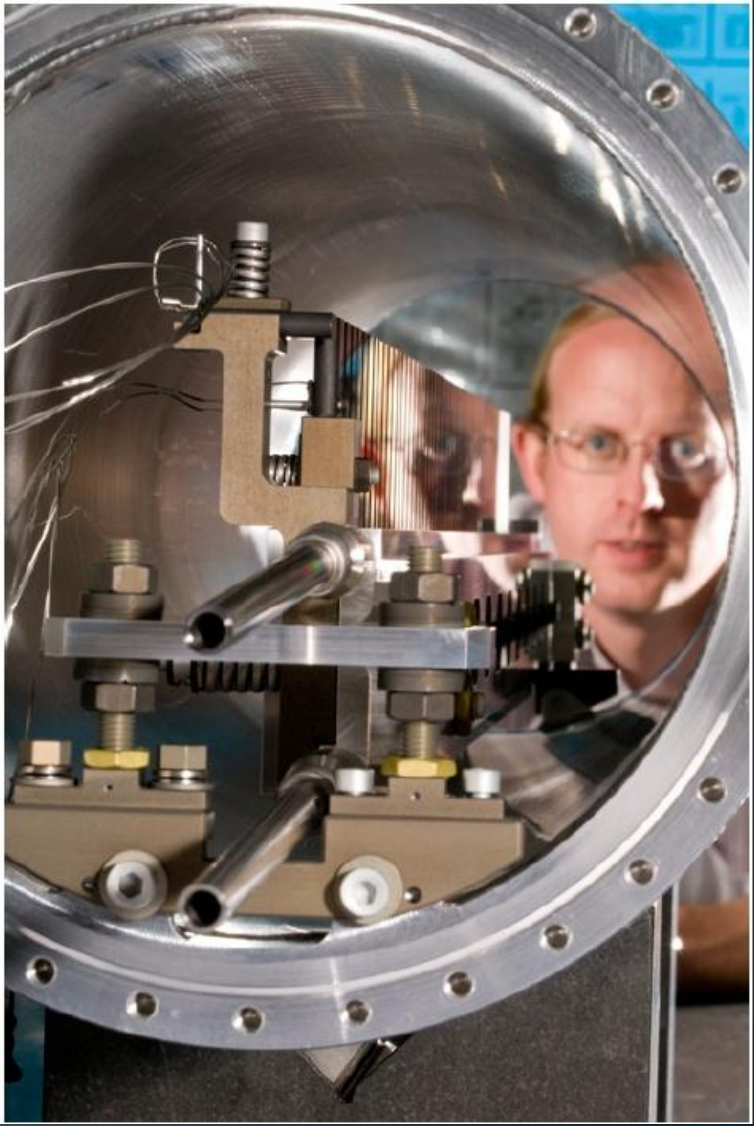
Target Hall Upgrades



Phil Adamson

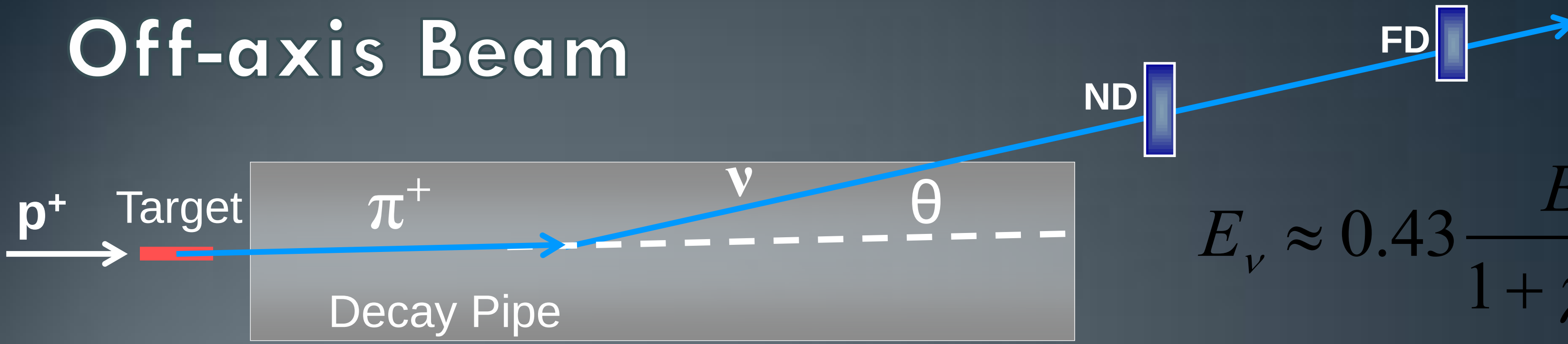


NOνA target



- NuMI target (top) must fit inside horn 1
  - Small, mechanically weak. Recent problems – failure of water cooling lines
- NOνA target (right) upstream of horn 1 (neutrino energy from off-axis angle)
  - Much more robust design. Water cooling 8 times further away from beam than NuMI

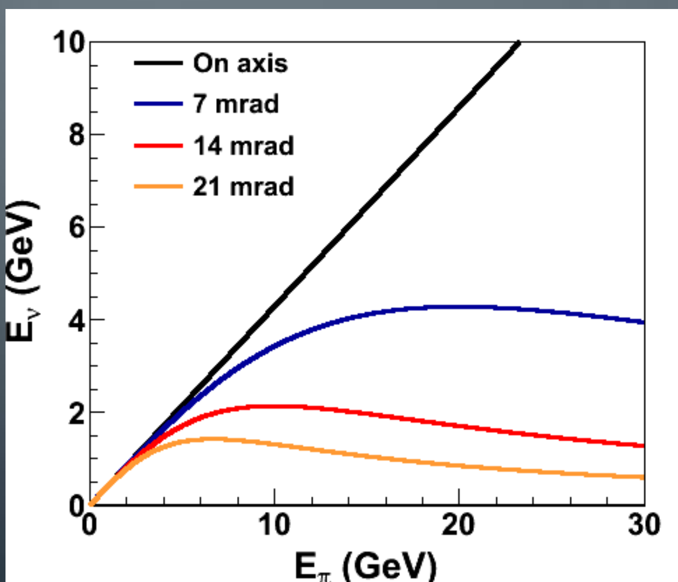
Off-axis Beam

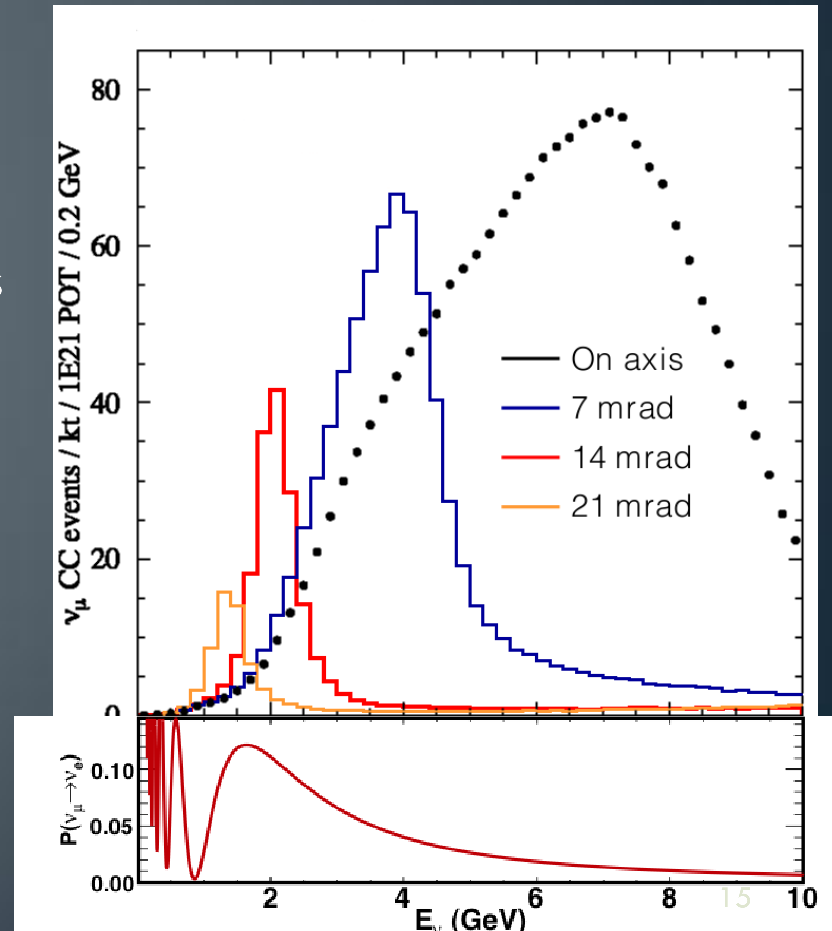


$$E_\nu \approx 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$

At 14 mrad off-axis, narrow band beam peaked at 2 GeV

- Near oscillation maximum
- Few high energy NC background events

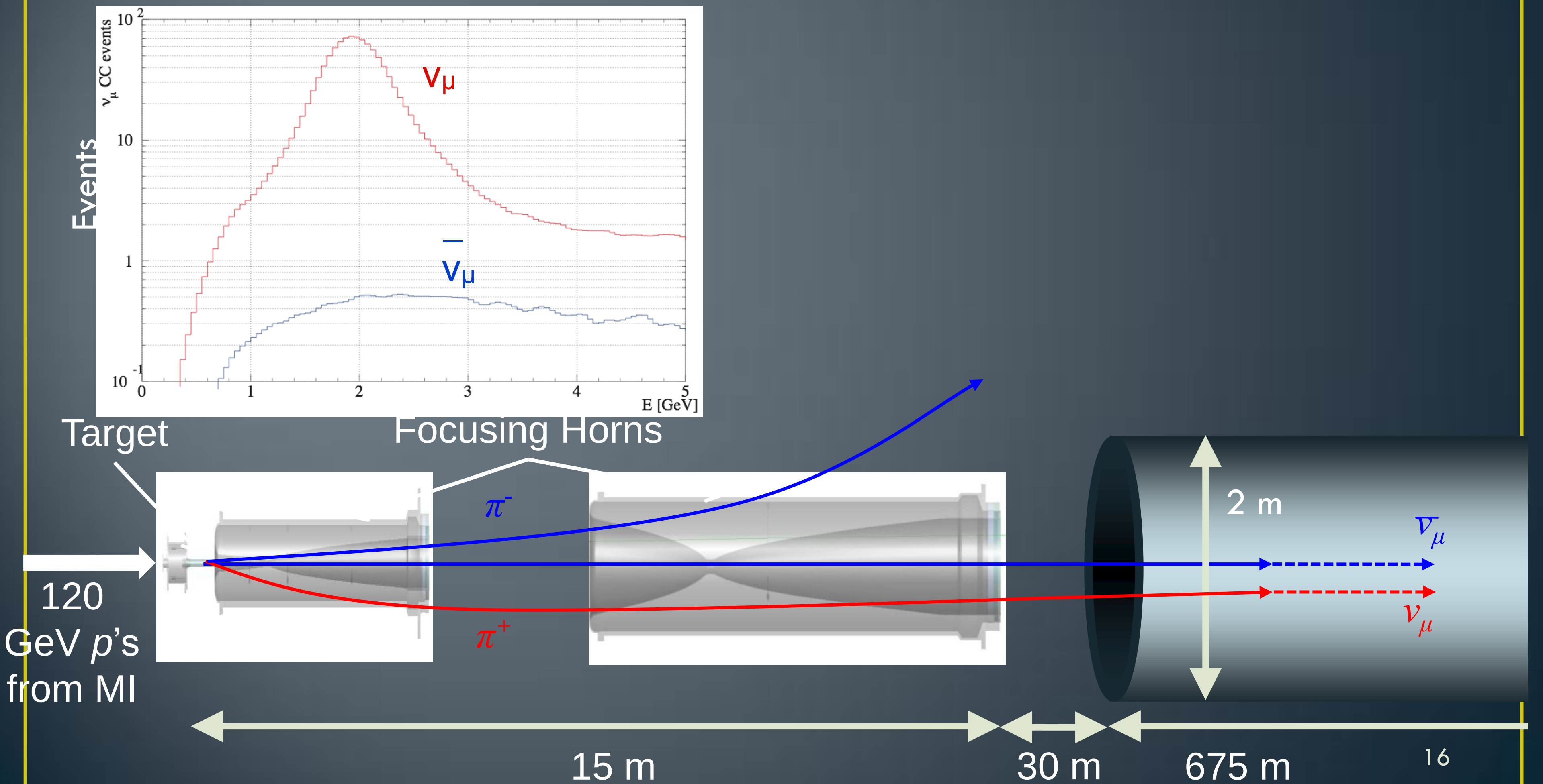




Making a Neutrino Beam@NOvA

Neutrino mode

Horns focus π^+, K^+



Making a Neutrino Beam@NOvA

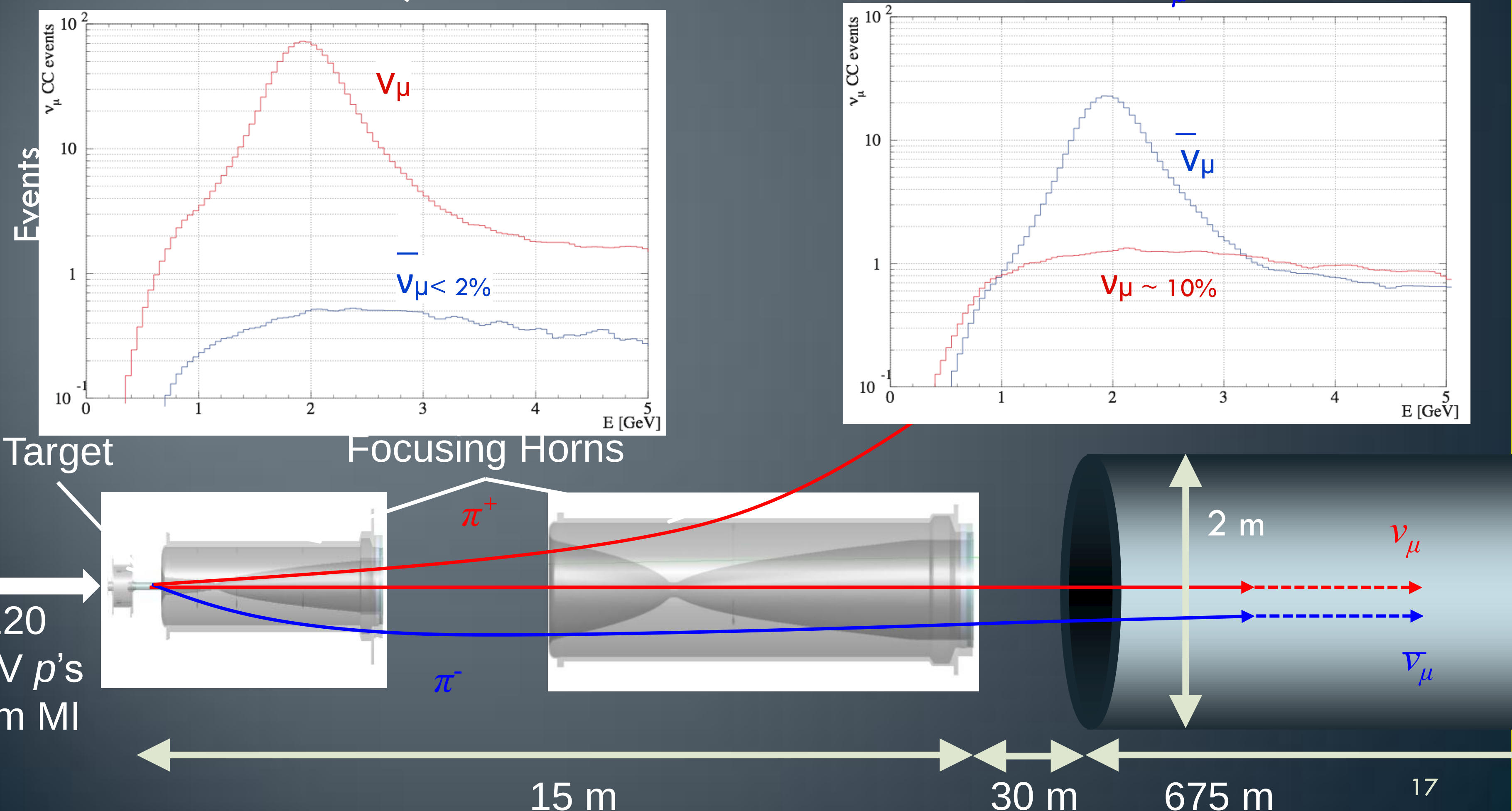
Neutrino mode

Horns focus π^+, K^+

Anti-neutrino Mode

Horns focus π^-, K^-

enhancing the $\bar{\nu}_\mu$ flux



The MINOS Experiment

(Main Injector Neutrino Oscillation Search)

MINOS Is a two detector long-baseline Neutrino Oscillation experiment

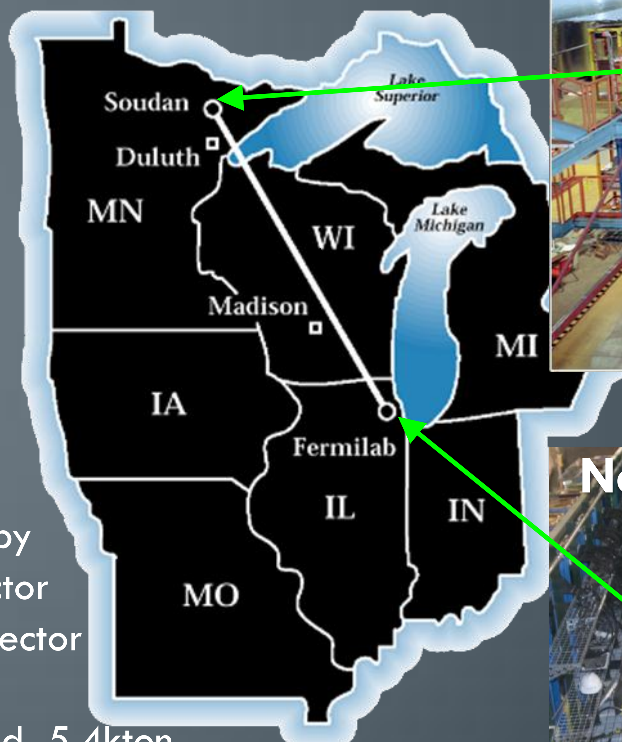
- 735 km baseline from Fermilab to Soudan,MN.

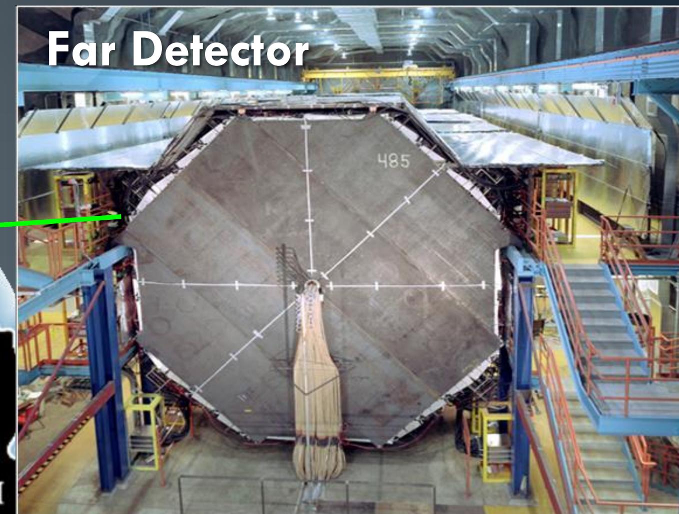
MINOS Near Detector

- Measure beam composition
- Measure ν energy spectrum
- 1km from source and 0.98kton
- 3.8 x 4.8 x 17 m^3
- 100 m underground

MINOS Far Detector

- Look for evidence of oscillations by comparing spectrum to Near detector
- <u>functionally identical</u> to Near detector
- 735 km from source
- 8 x 8 x 30m^3, 700 m underground, 5.4kton





The MINOS Detectors

Detectors are steel-scintillating sampling calorimeters

Having two functionally identical detectors minimizes errors due to beam and neutrino interaction uncertainties

Steel plane absorbers 2.54cm thick

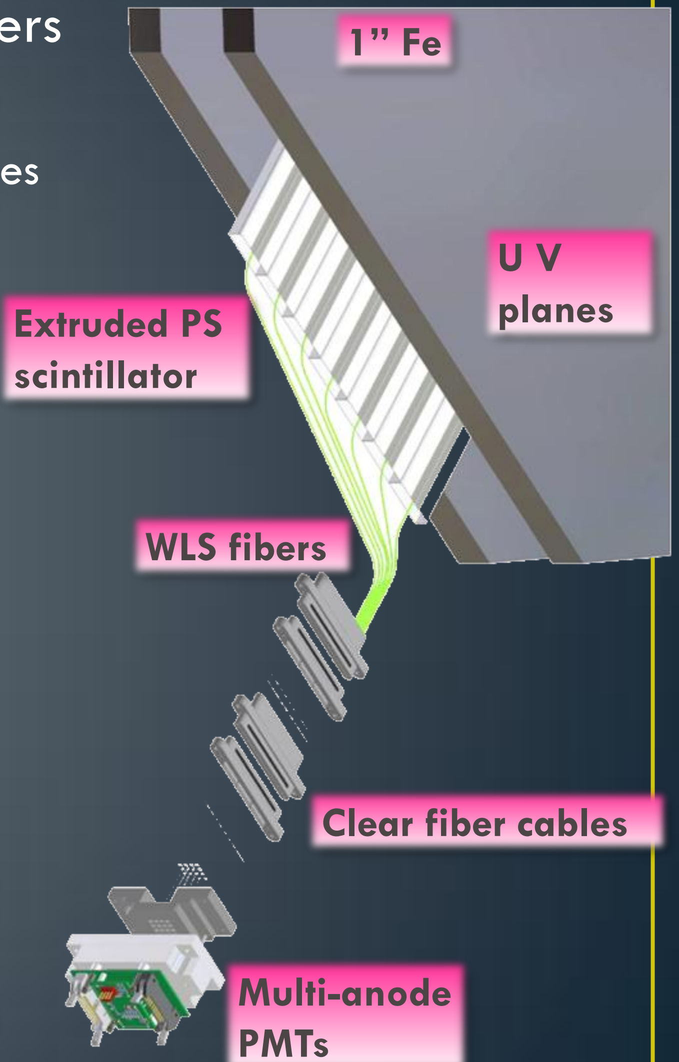
- Average <B>=1.3 Tesla (Toroidal)
- Good muon charge sign identification

Scintillating strips measure 4.1 x 1 cm^2

- strip width is 1.1 Moliere radius
- have embedded wavelength shifting fibers
- alternative planes are orthogonal to allow for 3-D reconstruction of events.

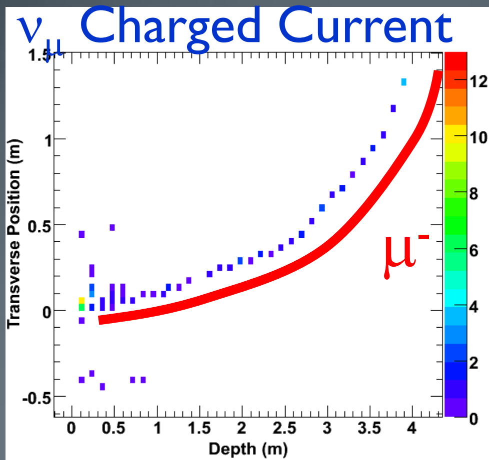
Detector Calibration

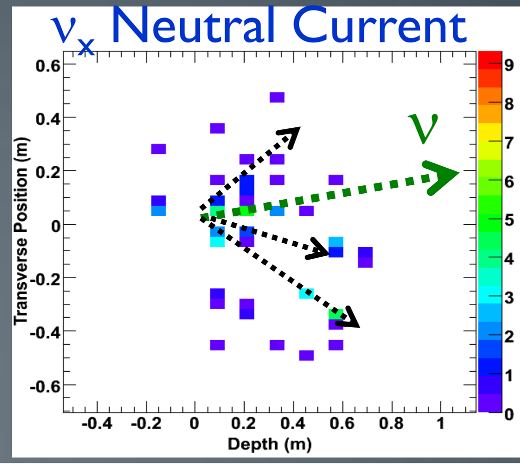
- Light injection to monitor hardware+electronics
- Cosmic muons used to monitor scintillator response
- CERN test beam detector set absolute Energy scale

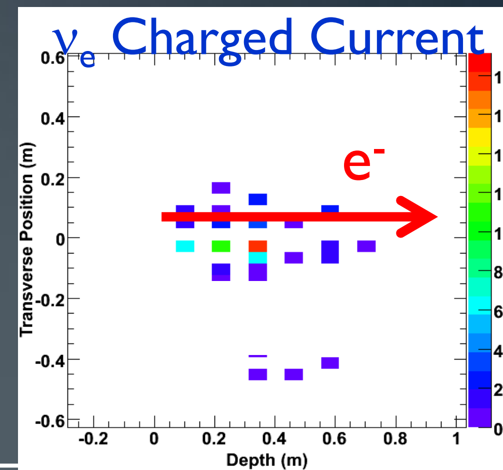


Neutrino Interactions in Detectors

transverse direction

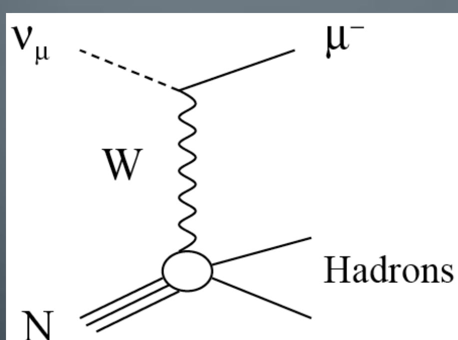


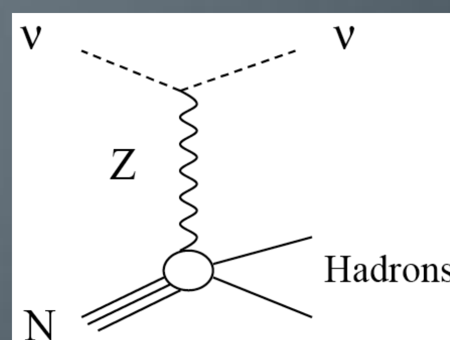


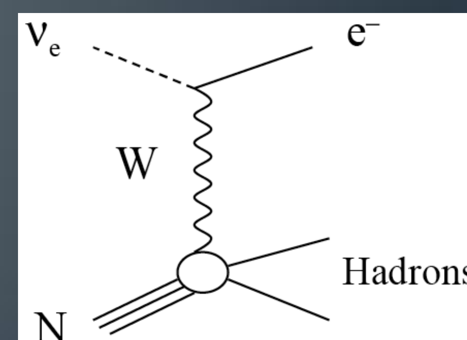


beam direction

color scale represents energy deposition





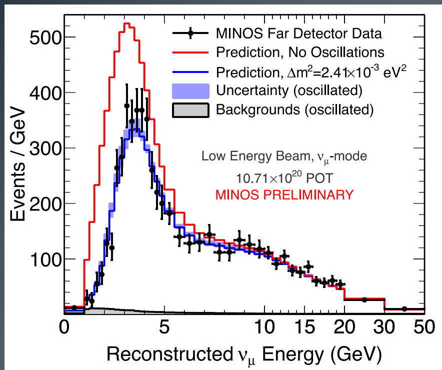


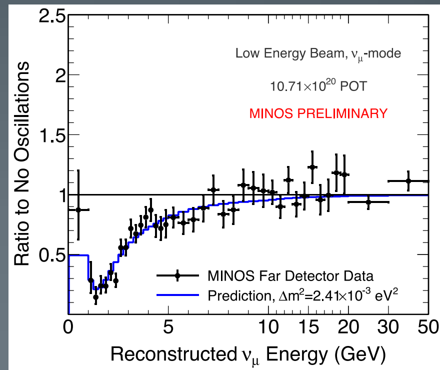
long μ track & possible hadronic activity at vertex

short with diffuse shower

short with compact EM shower profile

MINOS oscillation results (only disappearance)



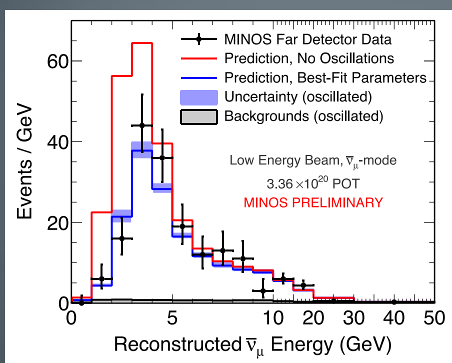


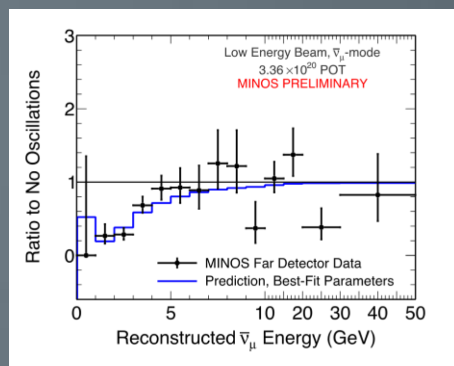
Muon Neutrino Oscillation Results

No oscillation Prediction: 3564 Observed: 2894

$$\left|\Delta m^2\right| = 2.41^{+0.11}_{-0.10} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\theta) = 0.94^{+0.04}_{-0.05}$$



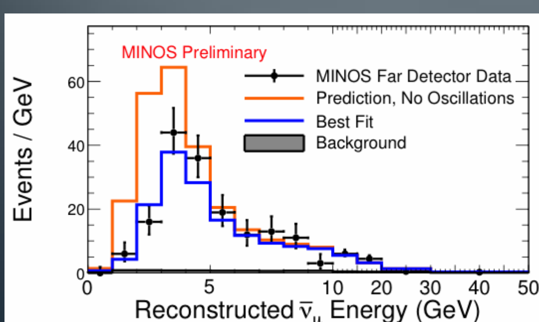


Muon Antineutrino Oscillation Results

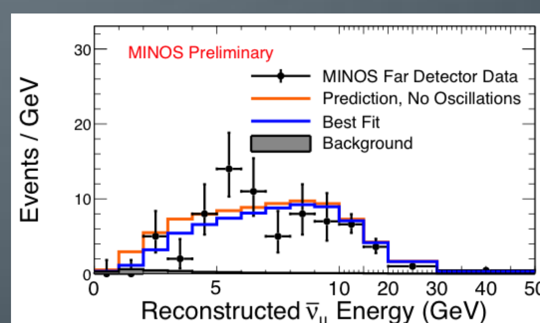
No oscillation Prediction: 312 Observed: 226

$$\left|\Delta \bar{m}^2\right| = 2.64^{+0.28}_{-0.27} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\bar{\theta}) > 0.78 \text{ (90\% C.L.)}$$



in antineutrino mode



in neutrino mode

Antineutrinos in Neutrino Mode

No oscillation Prediction: 536

Observed: 414

$$\left|\Delta \bar{m}^2\right| = 2.60^{+0.28}_{-0.23} \times 10^{-3}\,\mathrm{eV}^2$$

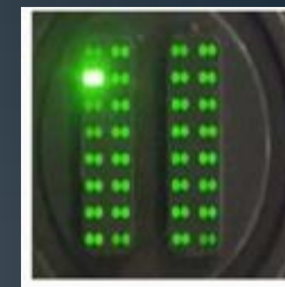
$$\sin^2(2\bar{\theta}) > 0.80 \text{ (90\% C.L.)}$$

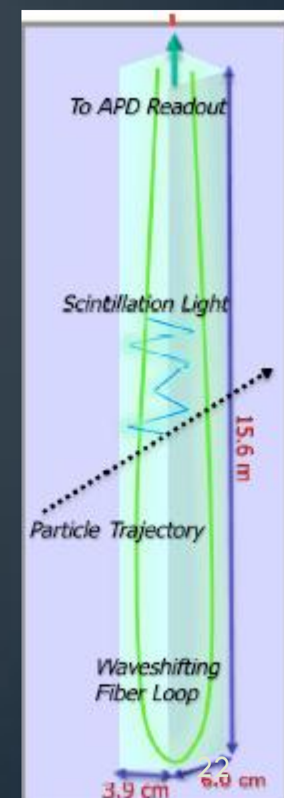
The NOvA detectors

- 14 kton Far Detector
  - 64 % active detector.
  - 344,064 detector cells read by APDs.
- 0.3 kton Near Detector
  - 19,104 cells (channels).
- Each plane just 0.15 X_0. Great for e^- vs π^0 .

32-pixel APD

Both ends of a fiber to one pixel

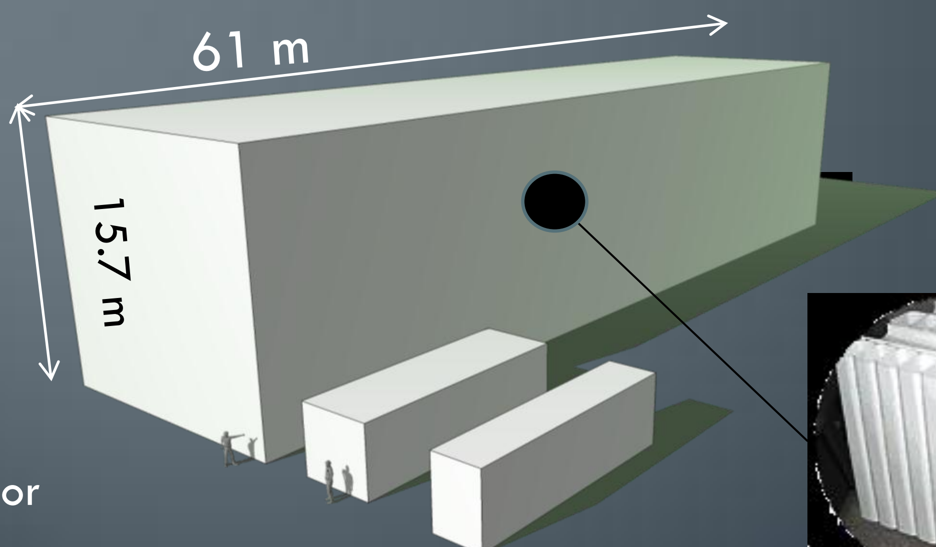




Far detector
14 kton
986 planes

Near detector
0.3 kton

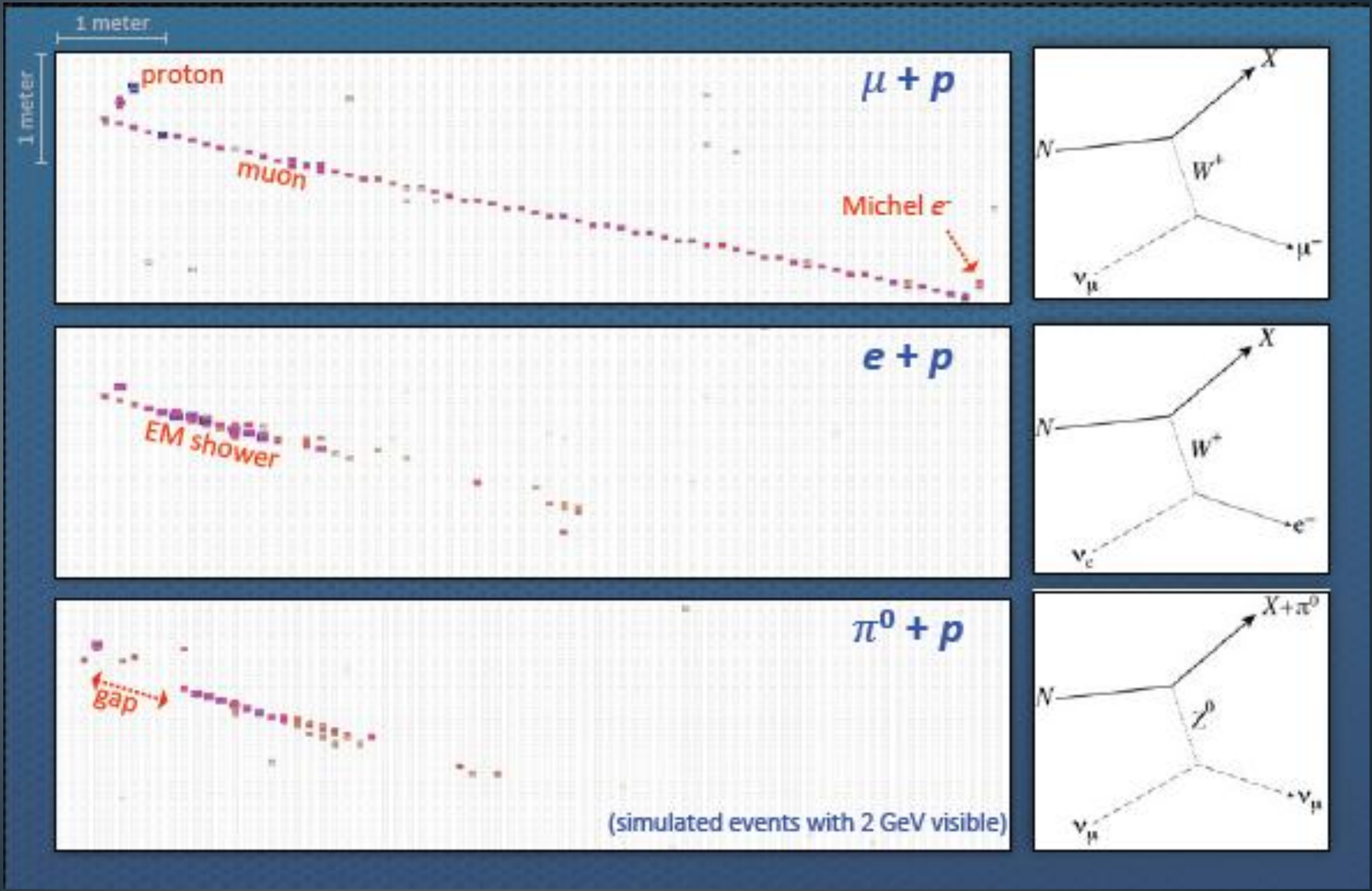
Prototype detecor
0.2 kton



MC Events in NOvA

Excellent granularity for a detector of this scale

X_0 = 38 cm (6 cell depths, 10 cell widths)



Far detector laboratory complete

Beneficial occupancy of Ash River laboratory on April 13, 2011

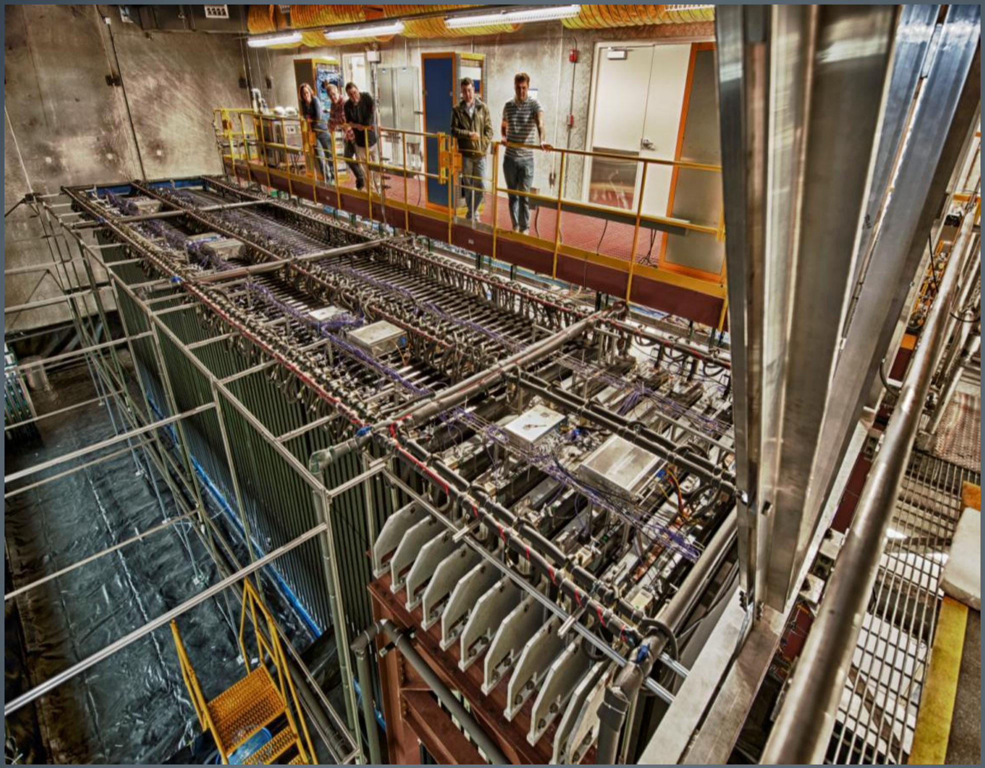
NOvA construction status

- Far Detector site construction is now complete.
  - The block pivoter is installed at the site.
  - Installation has started.
- Upgrade NuMI beam from
  - 350 kW to 700kW initiated May 1, 2012.
- Near Detector cavern excavation and assembly during shutdown.
  - Changed to 96 x 96 cell design to improve event containment.

NOvA construction status

- First layer of modules is permanently placed on the pivoter table at Ash River, MN - July 26, 2012
- First block installed on September 10
- Second block installed on October 3.
- 26 blocks to go
- Excavation of the Near detector cavern

Prototype Near Detector



"NDOS" (Near Detector on Surface)

- Component production, installation, and integration tests and adjustments
  - DAQ development
  - Calibration, simulation, reconstruction development using real data
  - Flux and cross sections

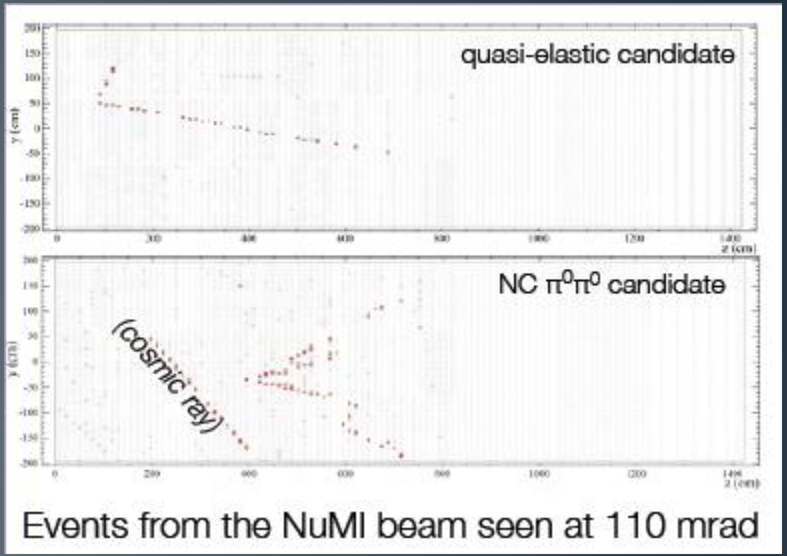
Located in two neutrino beams providing an early look at data and a chance to tune up DAQ, calibration, reconstruction, and analysis prior to first data from Ash River

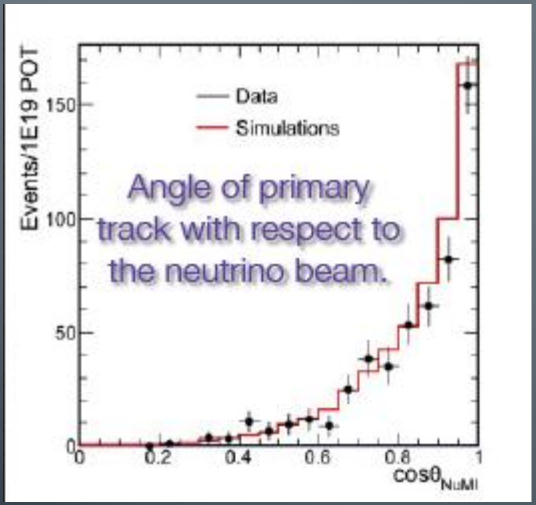
It saw neutrinos from NuMI beam at an off-axis angle of 110 mrad.

NDOS is located ~on the Booster Neutrino Beam (BNB) line, but the detector axis is rotated 23° with respect to the BNB beamline

NOvA Near Detector Prototype

- Near Detector Prototype installed on surface at Fermilab.
- 5000 neutrino events from the NuMI beam observed.
- Neutrino candidate data matches well to Monte Carlo.

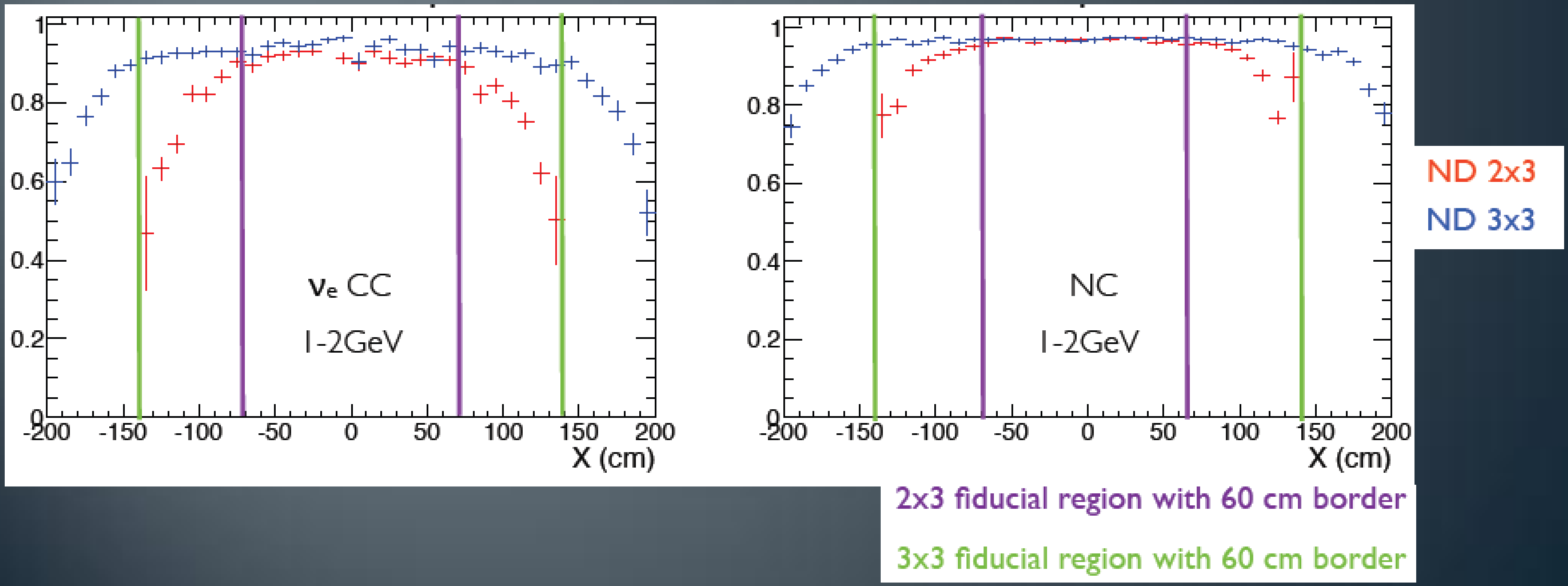




- Data is useful for detector operations.
- Benchmarking calibration, reconstruction and simulations.

Near detector change from 2x3 → 3x3

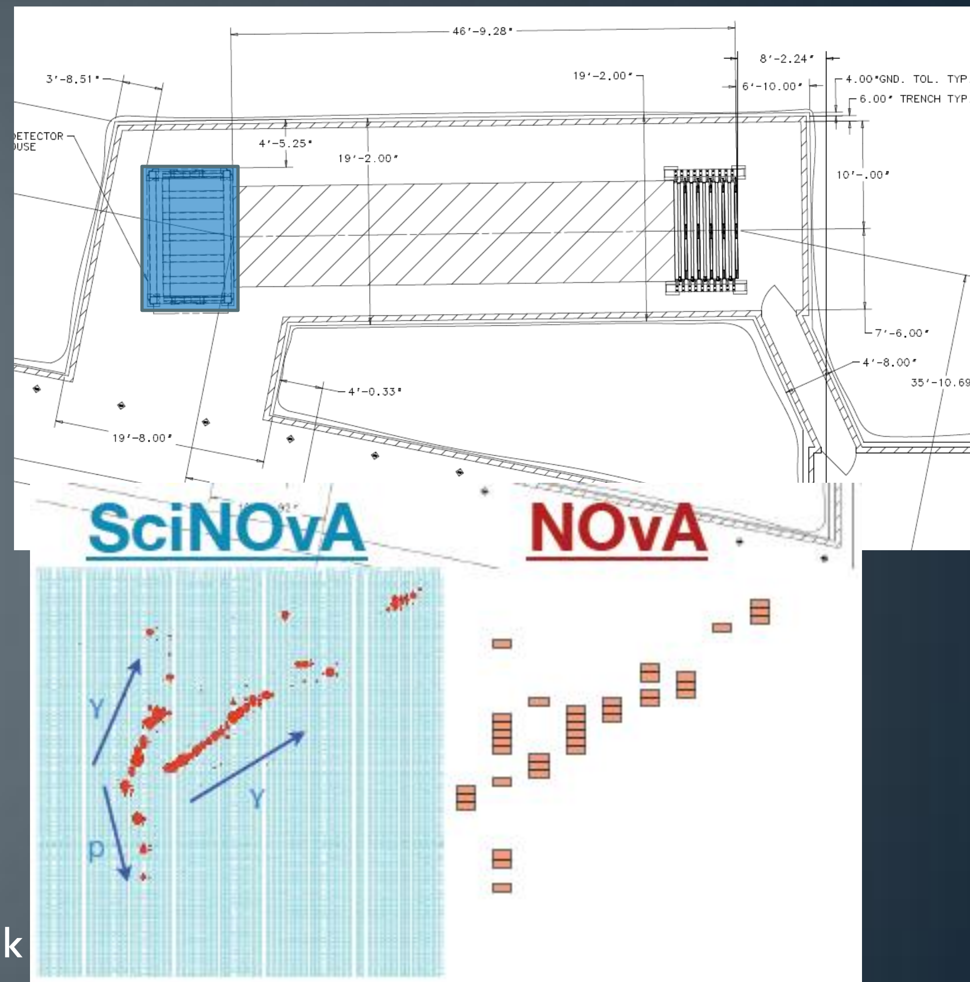
- Event containment differences
- In the NOvA Near Detector 82-87% of neutrino events are contained. Also Up to 10% of the NC lose a π^0.
- We do not expect these effects to be present in the Far Detector.



SciNOvA

- SciNOvA is an idea to build a fine-grained detector (patterned after the K2K and SciBooNE SciBar detector) and deploy it in front of the NOvA near detector to:

1. Aid in the detailed understanding of NOvA background event topologies
2. Measure neutrino cross sections, particularly CC QE di-nucleon correlations and NC π^0 production



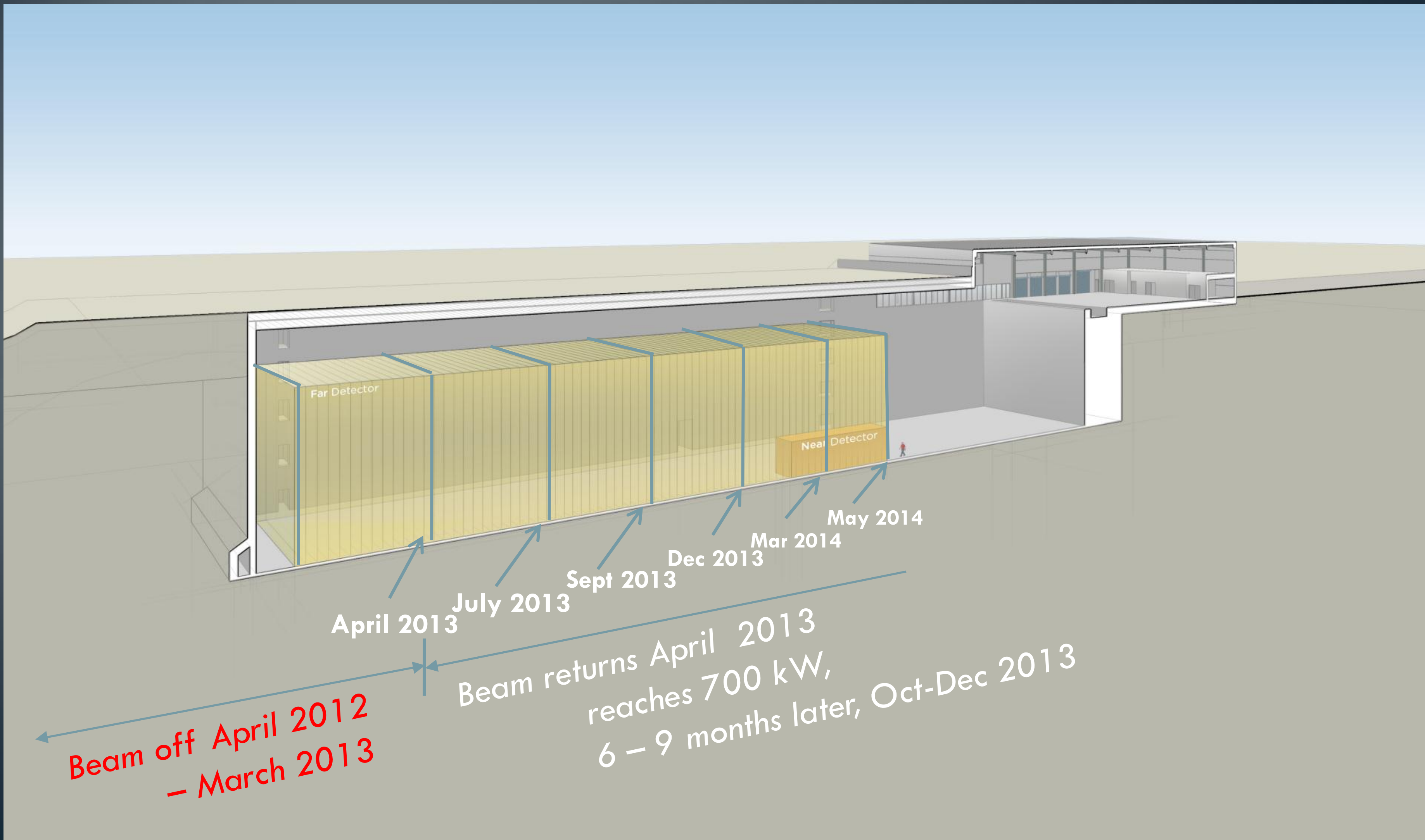
"Baseline" is SciBar from 2010 proposal 15k bars 1.3 cm x 2.5 cm x 290 cm
with 1.5 mm fiber to Hamamatsu M64 PMTs
using "IU IRM" readout boards
arranged in 64 alternating X/Y layers:

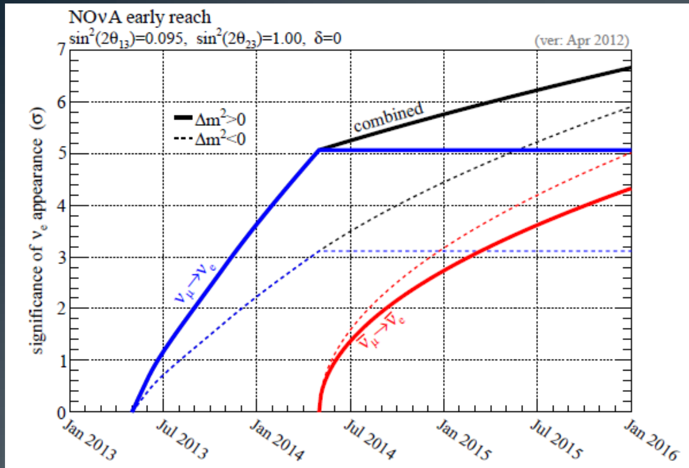
Currently not part of the NOvA project

Other options we considered

- The NOvA collaboration also considered other options but due to budget and/or technology issues we did NOT pursue them.
- Second near detector – with different L/E to cover the MiniBooNE low energy range.
- 2 km option for the near detector
  - Reduce the line source effect
  - Reduce the pile-up effect
- Magnetized detector
  - Determine the wrong-sign contamination of the beam.

Project Timeline (visualization)



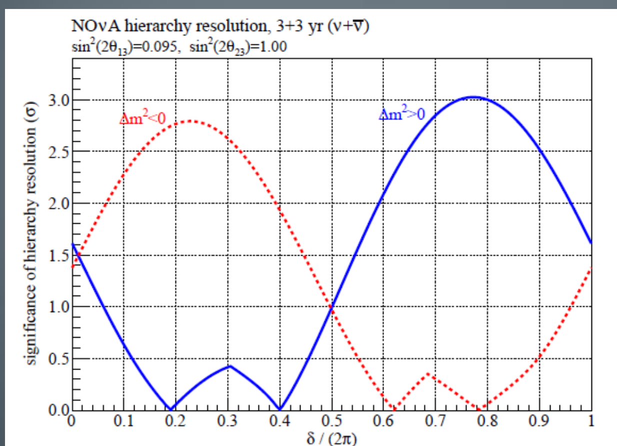


We will start with neutrino running:

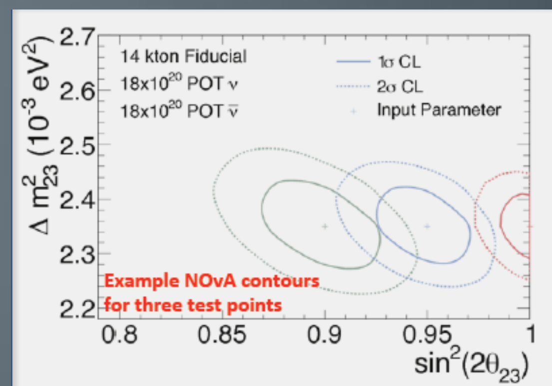
5σ observation of $\nu_\mu \to \nu_e$ in first year if normal hierarchy and then switch to anti-neutrino running as needed.

Nominal run plan 3 years in each mode at 6 x 10^{20} POT

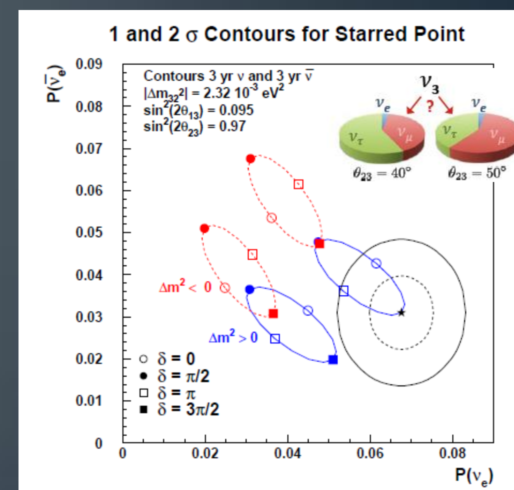
Beam	signal	Total Bkgd	NC bkgd	ν_μ CC bkgd	ν_e CC bkgd
neutrino	68	32	19	5	8
antineutrino	32	15	10	<1	5



- Significance of mass hierarchy resolution using a sample counting experiment.
- Energy fit provides improvement on the fully degenerate δ_{CP} values.



- NOvA's will do a few % measurement in Δm^2_{32} and $\sin^2 2\theta_{23}$.
- Improvement of one order of magnitude in $\sin^2 2\theta_{23}$.
- It might not be maximal.



If $\sin^2 2\theta_{23}$ is not maximal there is an ambiguity as to whether θ_{23} is larger or smaller than 45°.

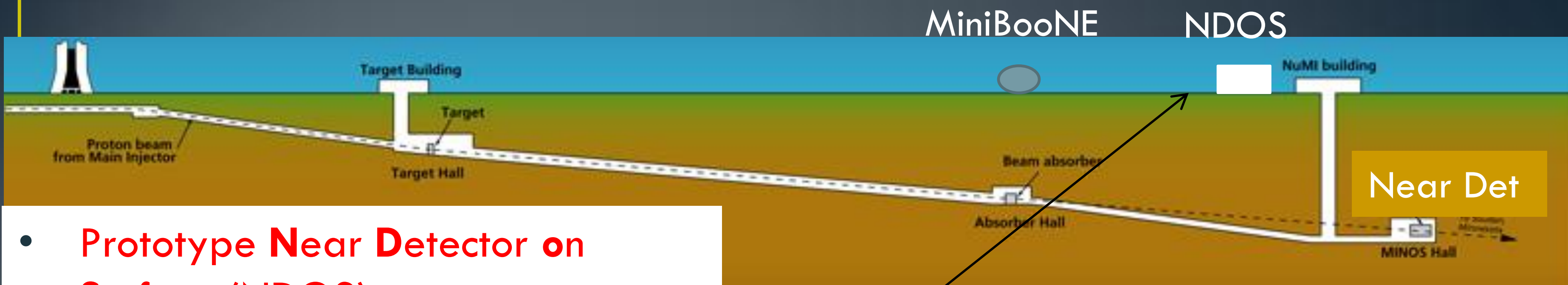
Summary

- MINOS collaboration will continue to take data after the NuMI upgrade as the MINOS+ experiment.
  - Inclusive cross section for neutrinos and antineutrinos **Phys.Rev. D81 (2010) 072002**
  - Charge current quasi-elastic scattering results – internal review
  - Coherent π^0 production – internal review

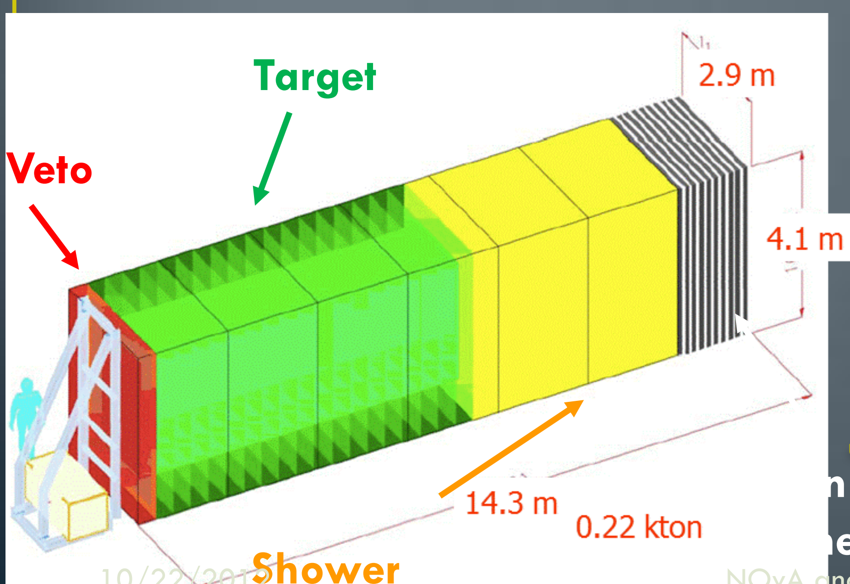
- NOvA very likely will present first cross section results from the near detector at next NuInt2014.
  - See poster by M. Betancourt (Study of Quasi-elastic interactions using the NOvA Near Detector Prototype)

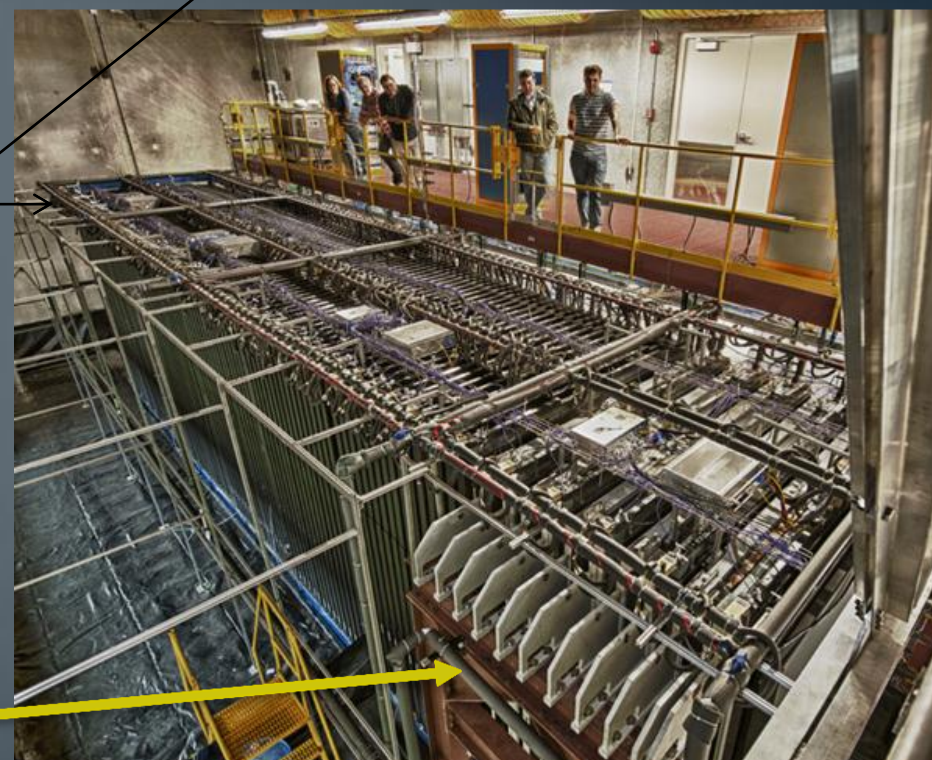
BACKUP

NOνA Near Detector Prototype (NDOS)

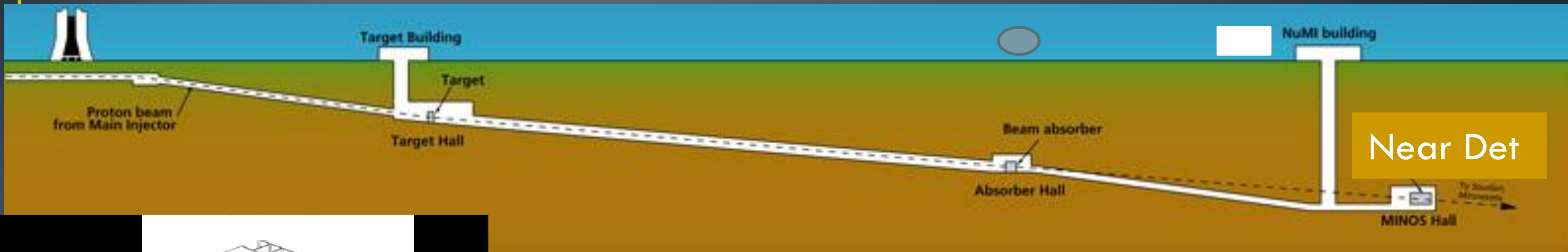


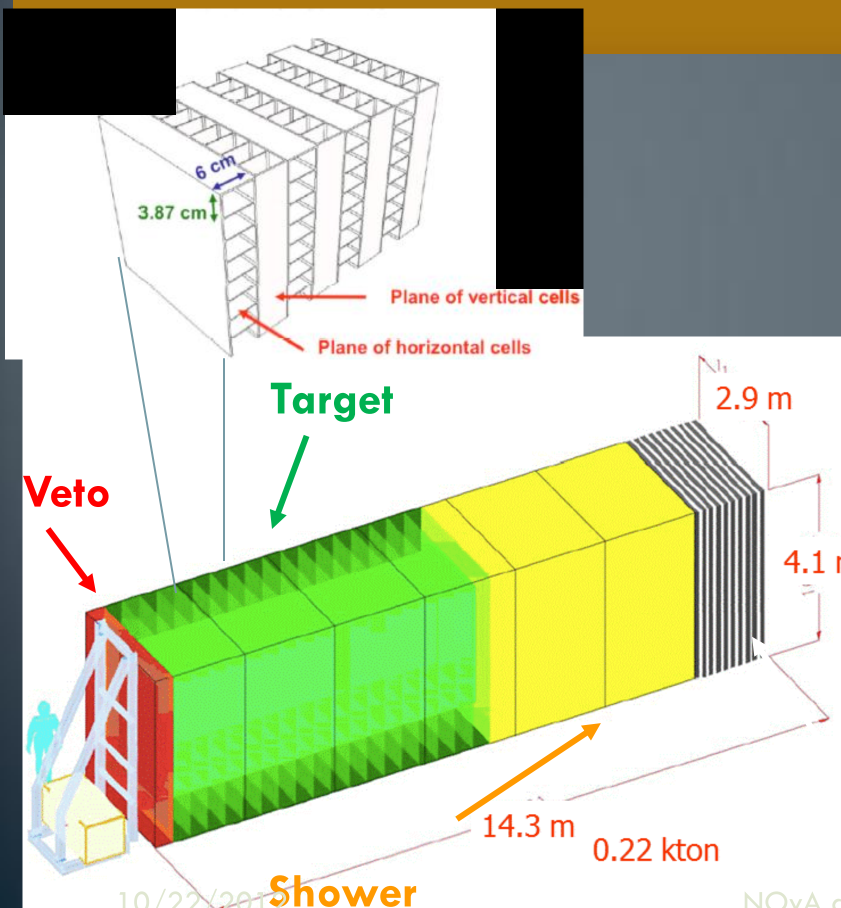
- Prototype **N**ear **D**etector **o**n **S**urface (NDOS) –
- Taking data since November 2010
- Prototype of the future Near Detector





NOvA Near Detector

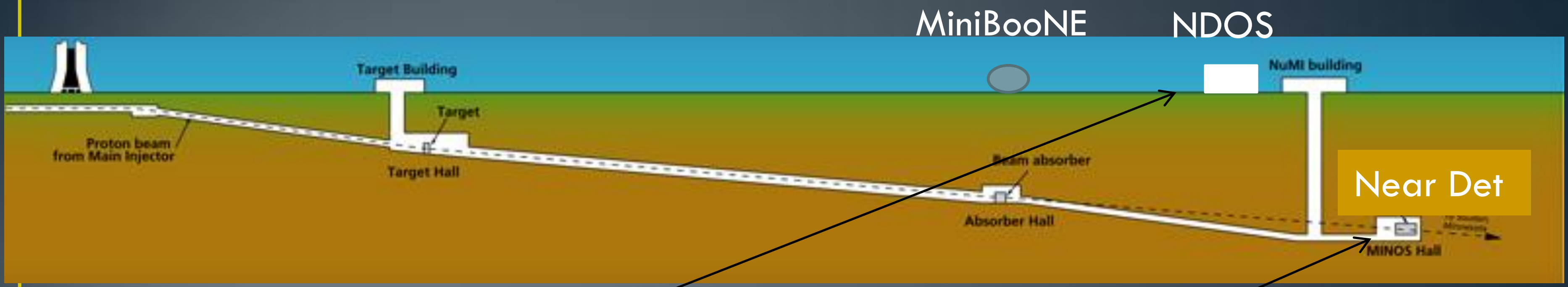




Near Detector

- 196 Planes (3m x 4m)
  + 10 Steel Planes ("Muon Catcher")
- 220 Ton
- 16000 cells
- Cosmic Ray Muon Rate:
  - ~50 Hz (105 m overburden)
- In-Spill Rate:
  - 10 μs duration every 1.33 s
  - **30 neutrino events/spill**

NOνA Near Detector Prototype (NDOS)



Prototype (NDOS)

- 196 Planes (3m x 4m)
  + 10 Steel Planes ("Muon Catcher")
- 220 Ton
- 16000 cells
- Cosmic Ray Muon Rate:
  - ~ 4 kHz (on surface)
- In-Spill Rate:
  - 10 μs duration every 2.2 s
  - 16 neutrino events/day (NuMI + BNB)
  - Partially instrumented

Near Detector

- 196 Planes (3m x 4m)
  + 10 Steel Planes ("Muon Catcher")
- 220 Ton
- 16000 cells
- Cosmic Ray Muon Rate:
  - ~50 Hz (105 m overburden)
- In-Spill Rate:
  - 10 μs duration every 1.33 s
  - **30 neutrino events/spill**

Prototype detector

Main goals are:

- Test detector design and prepare for far detector production.
- Develop DAQ system on custom design hardware
- Tune calibration procedures.
- Show electron neutrino selection and $e\backslash\pi^0$ separation.
- Verify cosmic background suppression.

Prototype detector

- NDOS collects data from NuMI and BNB beams

NuMI off-axis 110 mrad

- $<E_\nu> \sim 2$ GeV
- L ~ 850 m
- L/E~0.43 km/GeV

Booster (BNB) on axis but rotated wrt to the beam

- $<E_\nu> \sim 0.8$ GeV
- L ~ 650 m
- L/E~0.8 km/GeV

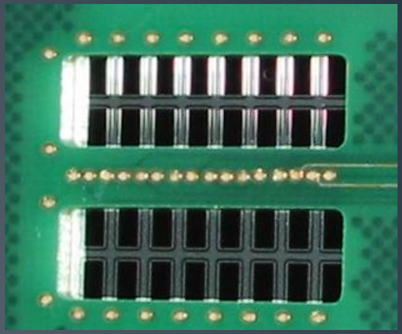
- Quasi-elastic cross section at 1 and 2 GeV.
- Study nuclear hadronization models and multinucleon production.

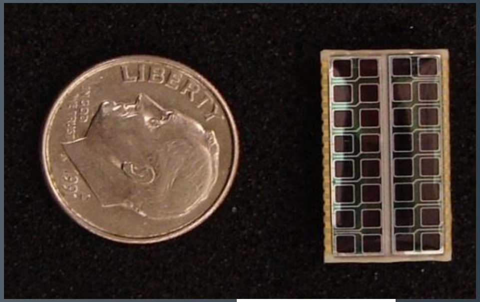
	PoT	NuMI	Cosmic Bg
Neutrino	5.6e18	253	39
Antineutrino	8.4e19	1001	69

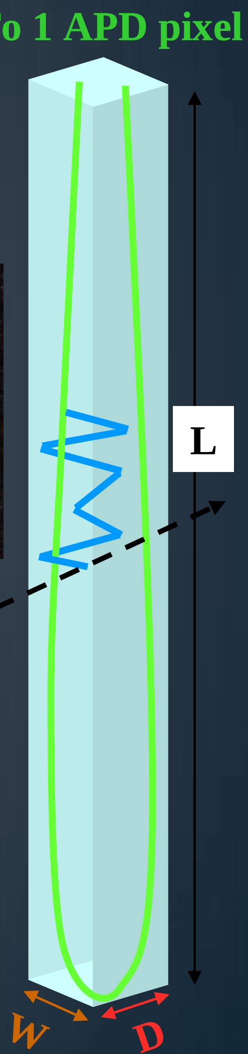
	PoT	BNB	Cosmic Bg
Antineutrino	3e19	222	92

Detector Components

- Liquid scintillator (3 million gallons)
    - Contained in 3.9cm x 6.6 cm cells of length 15.6 meters
    - 3.9 cm as seen by the beam
- Cell walls are rigid PVC (5 kilotons)
    - Loaded with 15% anatase form of titanium dioxide
    - Diffuse reflection at walls keeps light near (within ~ 1 m) particle path
- Looped wavelength-shifting fiber collects light (11,160 km)
    - Fiber diameter 0.7 mm
    - Fiber shifts wavelength to ~ 520-550 nm along the fiber
- Avalanche photodiode (APD) converts light to electrical signal (11,160 devices, ea. 32 pixels)
    - 85% quantum efficiency





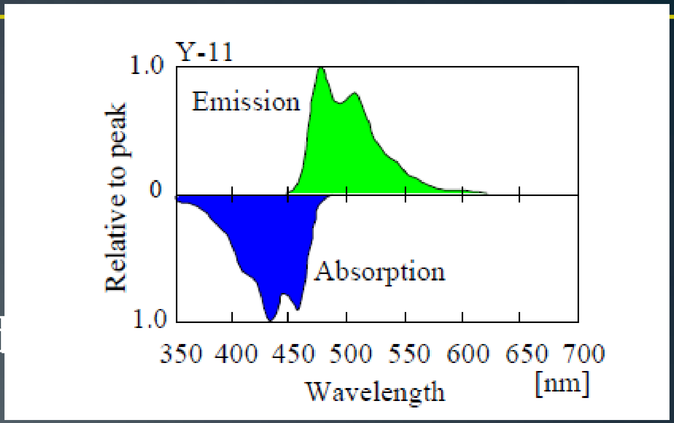


Liquid Scintillator Composition

- Liquid scintillator for NOvA is composed of a primary scintillant (pseudocumene) that gives off light at 300 nm,
- waveshifters (PPO & bis-MSB) that downshift the UV photons to longer wavelength to facilitate absorption by the wavelength shifting (WLS) fibers (convert the photons to 420 nm),
- anti-static agent (Stadis) that prevents the build-up of static electricity.
- The "fluor mix" + anti-static are dissolved in a mineral oil solvent

	component		mass fraction
solvent	*mineral oil*	liquid	94.90%
fluor mix	*pseudocumene*	liquid	4.99%
fluor mix	*PPO*	powder	0.110%
fluor mix	*bis-MSB*	powder	0.0015%
anti-static agent	*Stadis-425*	liquid	0.0010%
	Total		100.0%

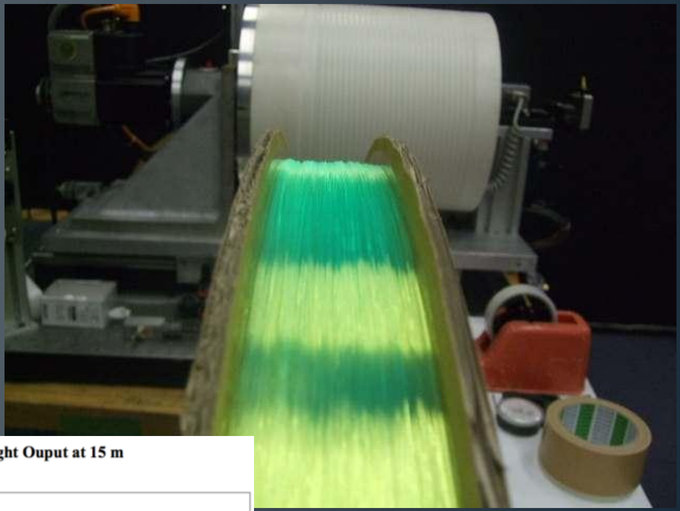
WLS Fiber

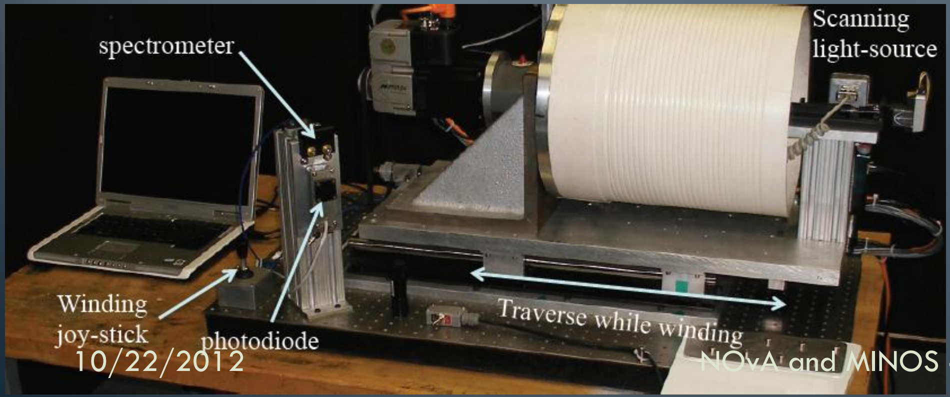


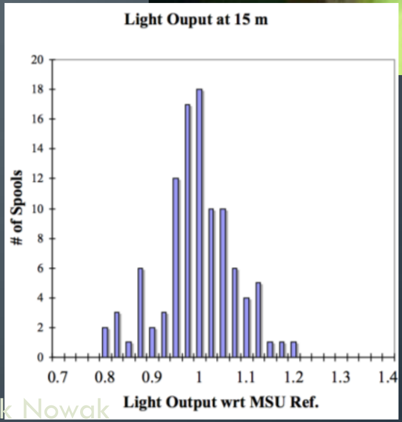
Need ~ 12,000 km of 0.7 mm diameter wavelength shifting fiber from Kuraray. So far ~10% received and tested

K27 dye @ 300 ppm, S-type

- MSU Quality Assurance Scanner (duplicate at Kuraray factory)
  - Fiber wound on a drum in a 27 m long groove with holes on 1 m intervals
  - Fiber is NOT cut from the spool,
  - Light source illuminates fiber from within the drum
  - Total light output (photodiode) and spectrographic scans, each ~ 1 minute







APD Description

- APD is a classic linear APD manufactured by Hamamatsu operated at a gain (M) of 100
  - S11211(X) custom variant of commercial S8550 SiAPD
- Operating temperature is -15°C to keep shot noise at the same level as the amplifier noise
- Signal-to-noise > 10 for muon at far end of a 15m long cell
- Both ends of the fibe

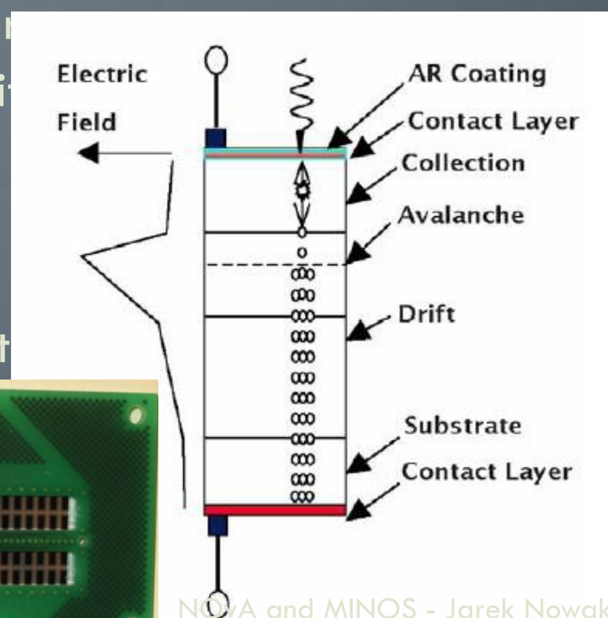
in each cell are read wi

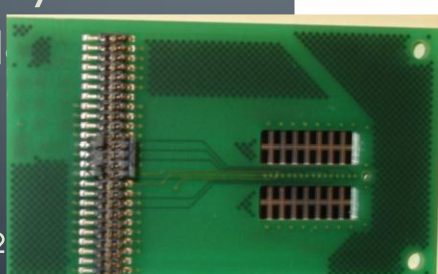
a single APD

- 32 APDs in a single

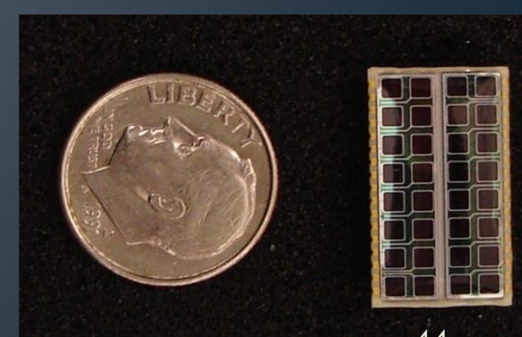
4 × 8 array to readout

one modul

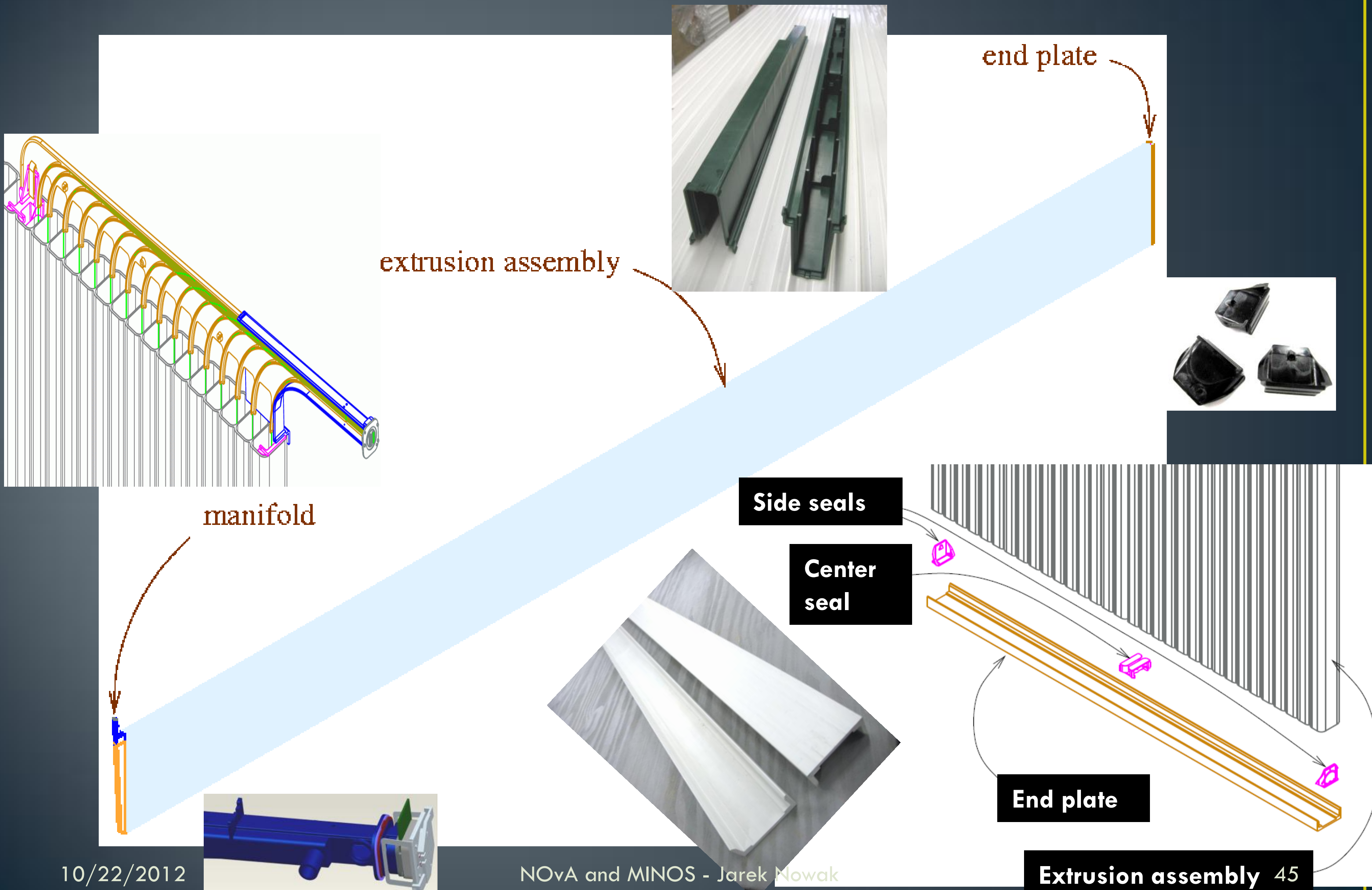




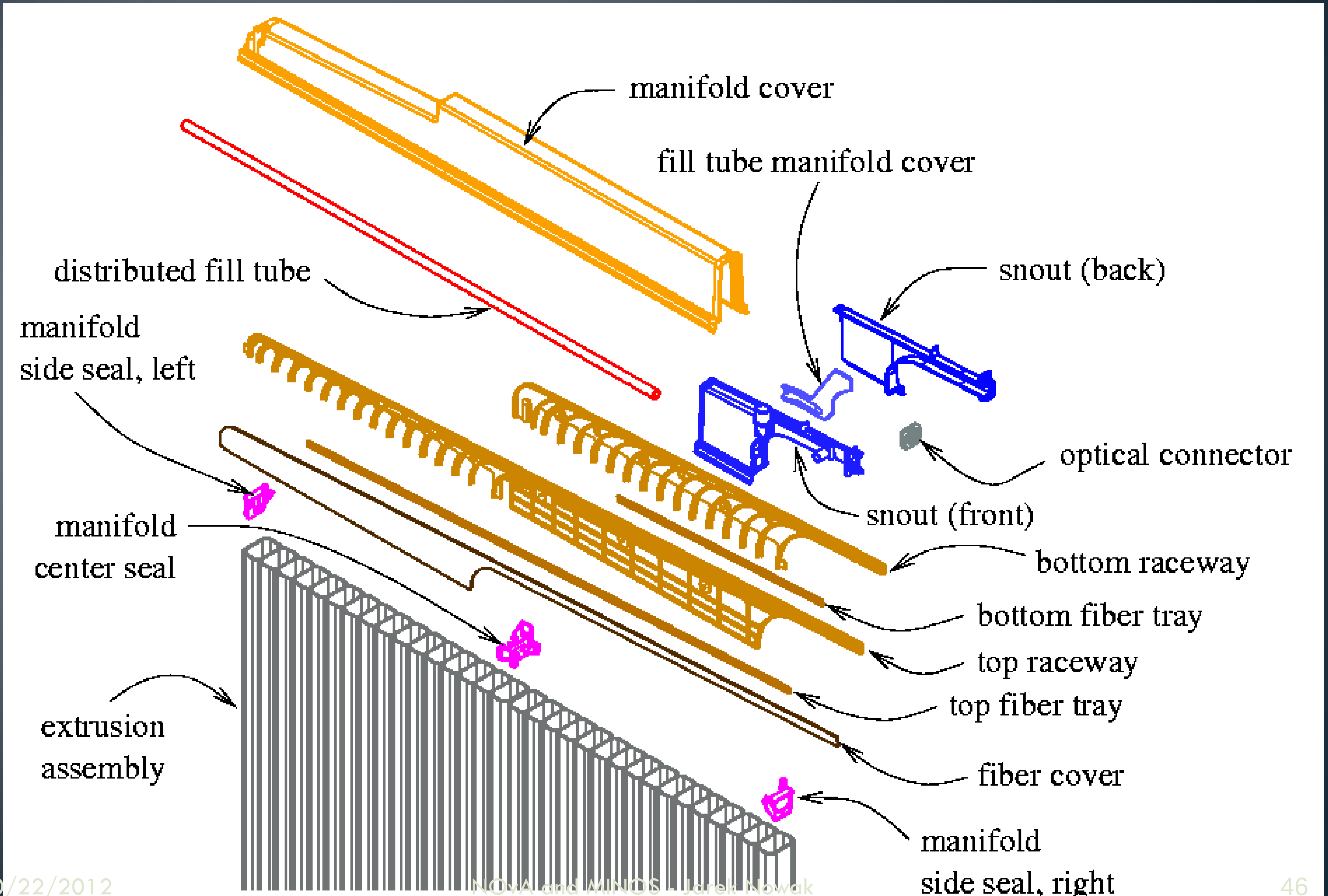
Manufacturer	
Pixel Active Area	1.95 mm × 1.0 mm
Pixel Pitch	2.65 mm
Array Size	32 pixels
Die Size	15.34mm × 13.64mm
Quantum Efficiency (>525 nm)	85%
Pixel Capacitance	10 pF
Bulk Dark Current (I_B) at 25 C	12.5 pA
Bulk Dark Current (I_B) at -15 C	0.25 pA
Peak Sensitivity	600 nm
Operating Voltage	375 ± 50 volts
Gain at Operating Voltage	100
Operating Temperature (with Thermo-Electric Cooler)	-15°C
Expected Signal-to-Noise Ratio (Muon at Far End of Cell)	10:1
APD channels per plane	384
APD arrays per plane	12
Total number of planes	930
Total Number of APD arrays	11,160
APD pixels total	357,120



Module Architecture

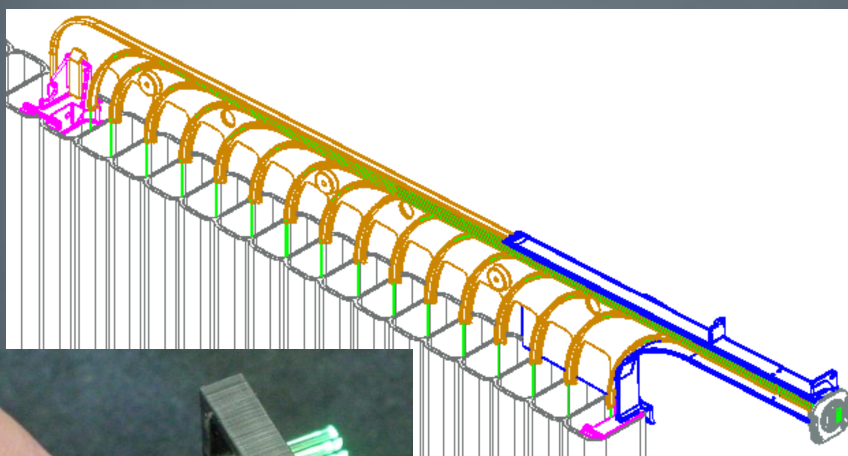


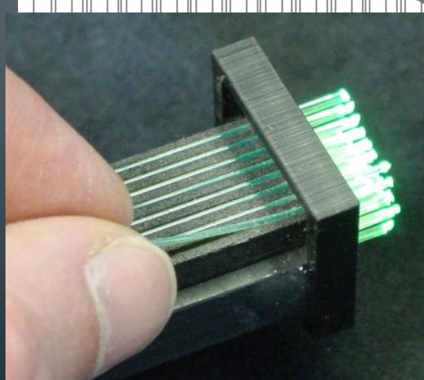
ND Manifold Architecture



Raceway Functionality

Face of optical connector

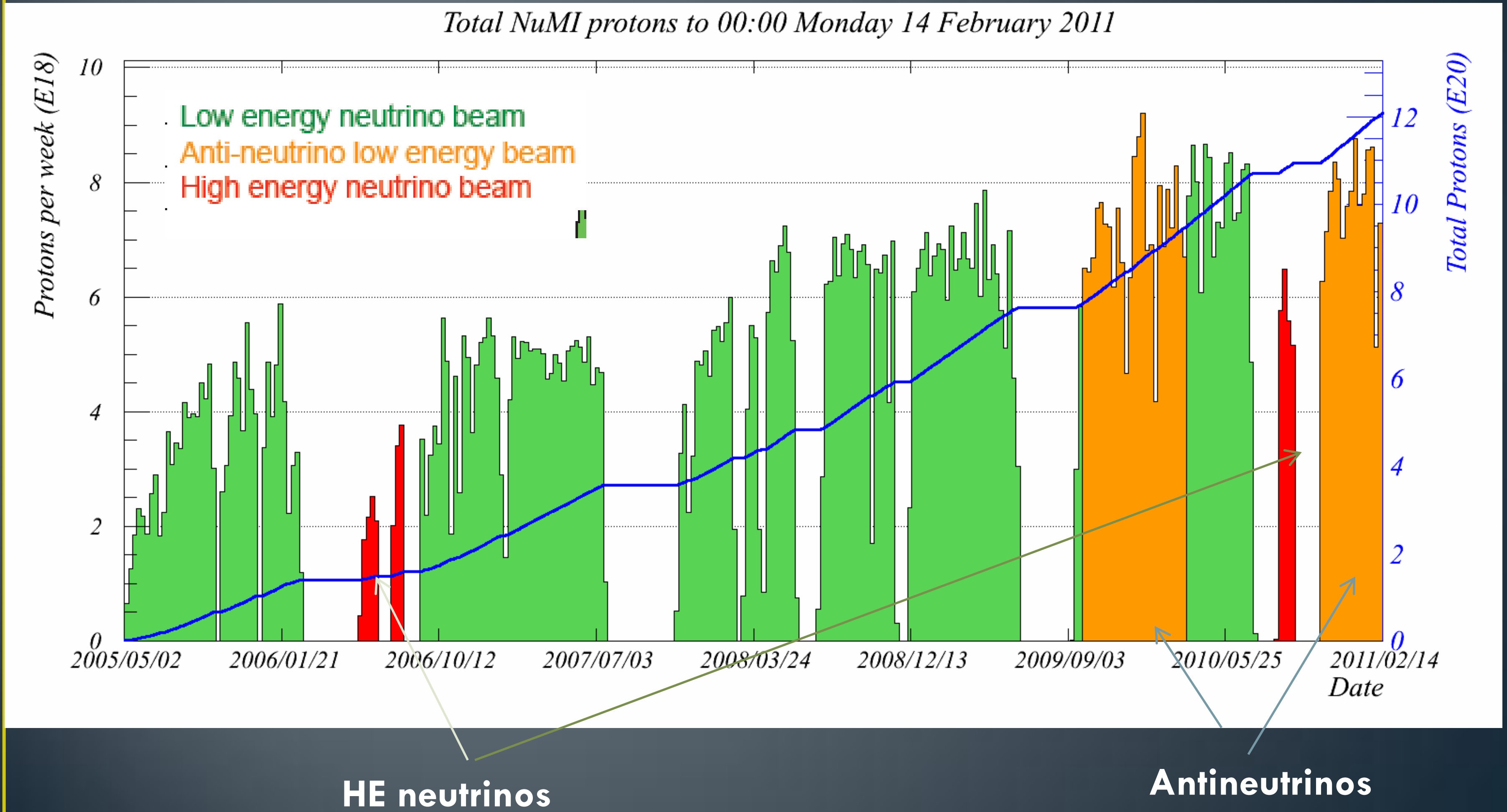




Threading fibers into opt conn

- Registers fibers in optical connector
- Guarantees acceptable bend radius
- Shields fibers from events in manifold
- Facilitates assembly

Beam Data Analyzed

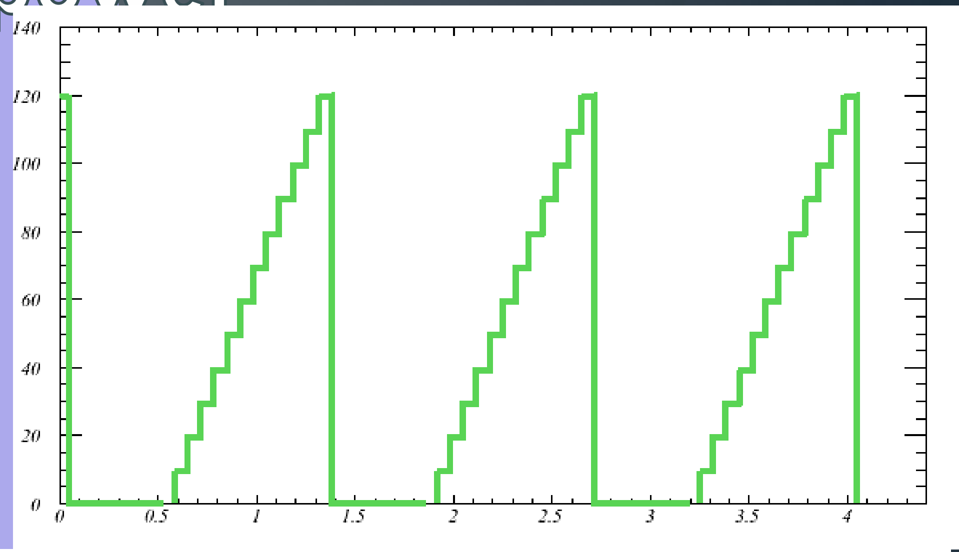


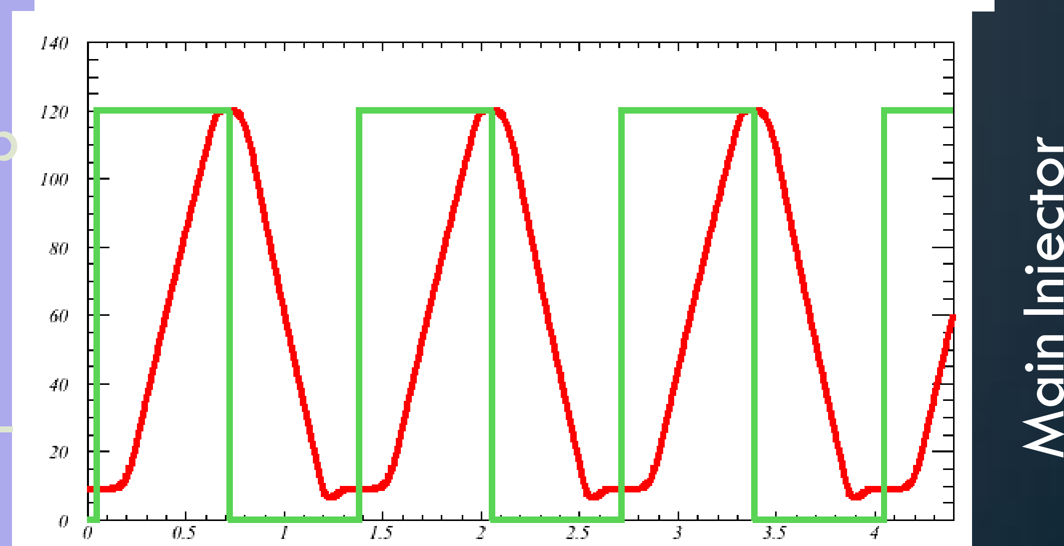
NOνA upgrades

- Increase NuMI primary proton beam power
  - 330 (380) kW -> 700 kW
- Additional focus on loss control
  - Double the beam power
  - Same tunnels
- Change neutrino beam energy (focussing)
  - Optimize flux at off-axis NOνA location

Increasing beam power

- Move slip-stacking to recycler
- 11 batch -> 12 batch
- Increase Main Injector ramp rate (204 GeV/s -> 240 GeV/s)
- 330 (380) -> 700kW with only ~10% increase in per-pulse intensity





So need to rebuild recycler

- Remove:
  - Old transfer lines
    - Small aperture (pbar: $6\pi/2\pi$, protons: $15–20\pi$)
  - Stochastic cooling
  - Electron cooling
    - Pelletron
    - Rebuild MI-30 with FODO lattice
  - Various odds and ends that might be aperture restrictions
- Add:
  - New injection line from MI8 to recycler
  - New RR->MI transfer line
  - 53 MHz RF system for slip-stacking
  - Instrumentation
    - BPMs
    - Low-mass Ti multiwires
    - IPMs
  - Must maintain vacuum at $10^{-10} – 10^{-11}$ torr (TSPs)

New MI-8 line

- Switched dipole at 849
  - ADCW (wide-gap modification of old ADC magnet)
- Strontium Ferrite permanent magnet dipoles like rest of MI-8
- Two Samarium Cobalt dipoles (space constraints)
- Strontium Ferrite recycler quads, powered quad trims for lattice matching

Installation in MI8

- 1-week shutdown in March 2011
  - Electric company replacing switchgear offsite
- Installed first PDD magnet in new MI8

Rebuild 30 straight

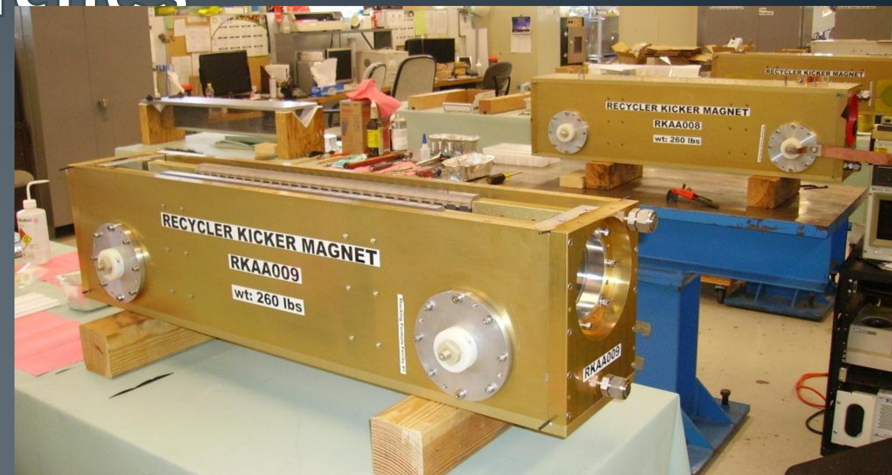
- New permanent quads for 30 straight in recycler
  - Total cost cheaper than re-making existing quads
  - ALARA

53 MHz RF in Recycler

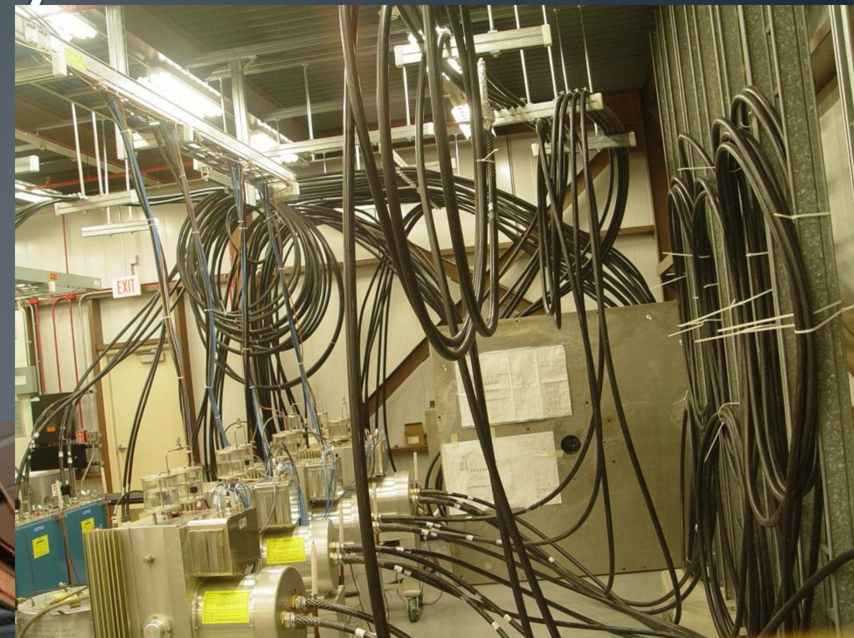
- Build 3 RF cavities
  - A, B and hot spare
  - 150 kV per cavity
  - Operating range: 52.809 MHz ± 1260 Hz
  - 10 KHz fast (~40 μs) phase shifters from Proton Driver
- Recycle PAs and modulators from Tevatron
- LLRF close to a copy of MI system

11 batches -> 12 batches

- Currently place 81 bunches every 86 in MI
- For NOνA, place 81 bunches every 84 in Recycler. (84 = 588/7)
- Faster rising/falling edges -> many short kickers (6)
- Already have 7 RKA magnets in MI: Gap Clearing Kicker system for loss control

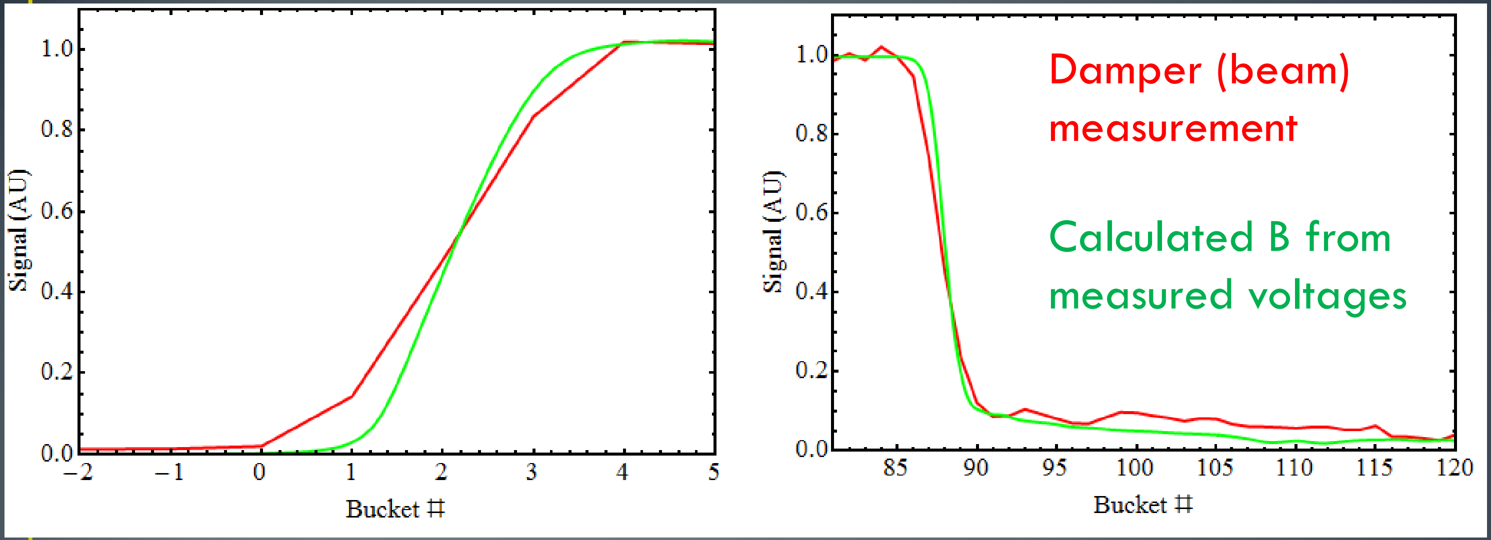


Gap Clearing Kicker System



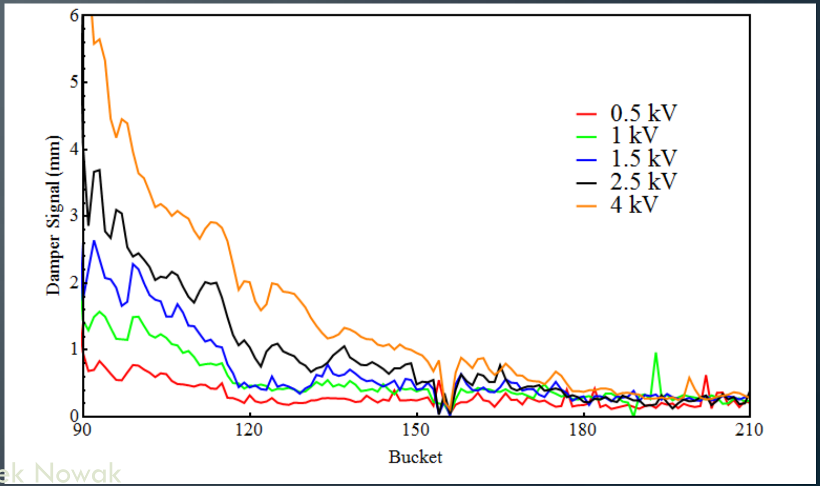
6/7 magnets will move up to recycler for NOvA

GCK measurements

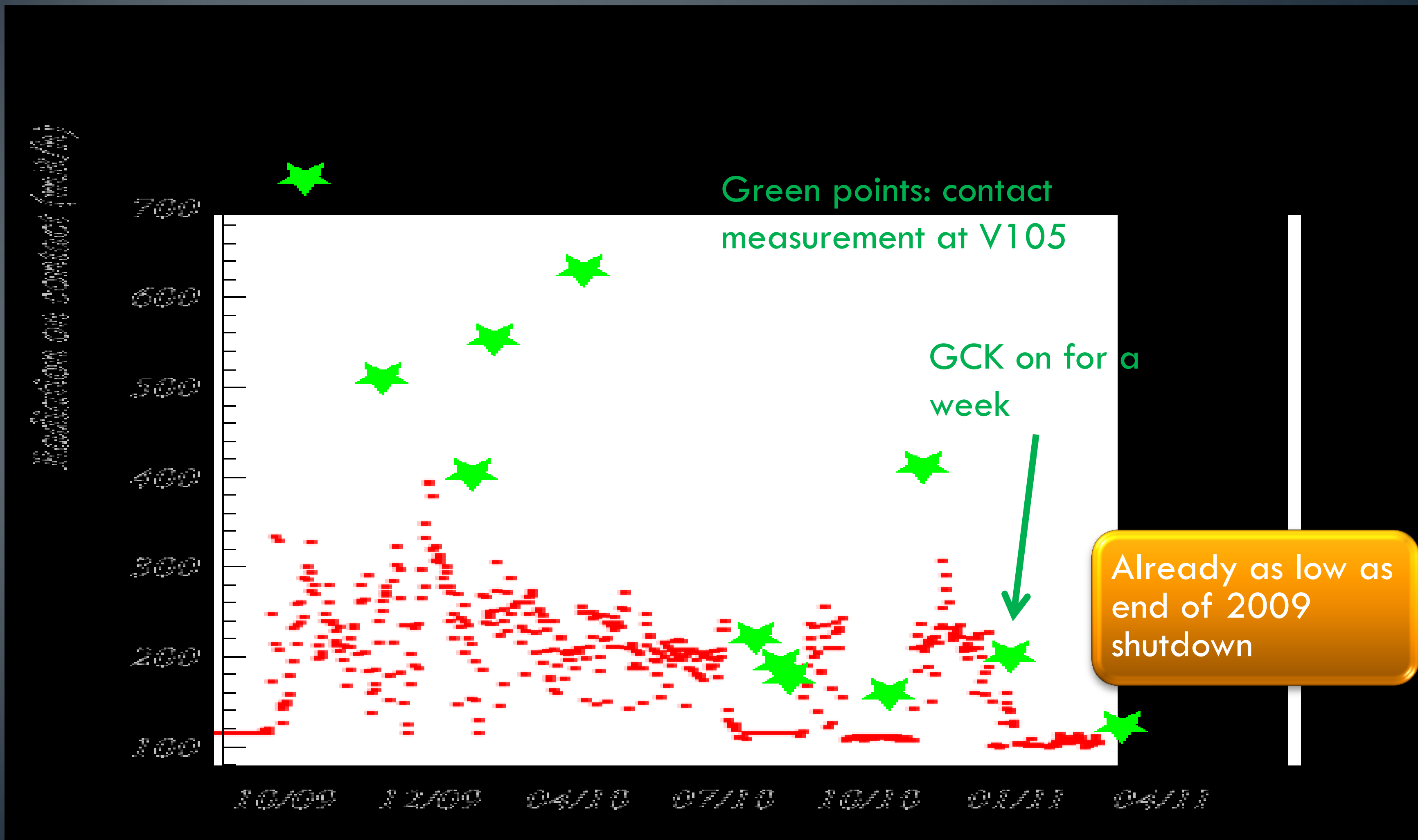


- Edges within specification
- Slower edge in damper measurement might be artifact

- For recycler, building "tail bumper" to cancel tail
- Tail measurement similar to electrical measurements (good)

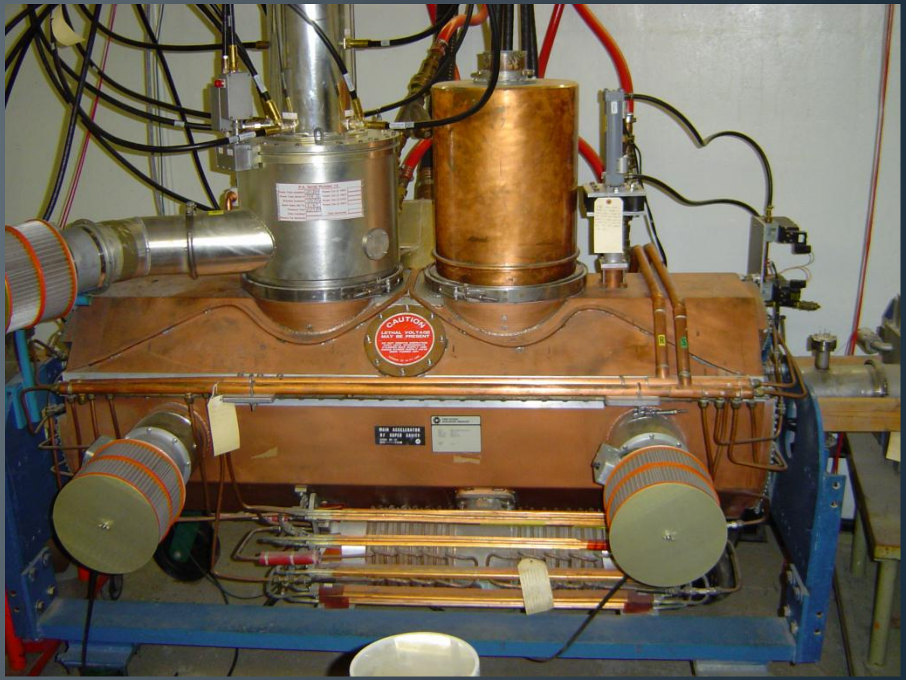


GCK reducing local losses



Increase MI ramp rate

- 2 new MI cavities to maintain bucket area
- New transformer for vertical quad bus
- Increased heat load on cooling ponds
  - Will need more cooling for summer – study underway looking at future cooling needs (not just NOνA)
    - More ponds?
    - Run a chiller in summer?
    - Shade ponds?



Beamline upgrades

- Increase rep rate
  - 2.2s (2.0s) -> 1.33s
- Replace 5 3Q120 quads with ones from A150 beamline (better cooling)
- Upgrade magnet power supplies
  - Faster ramp
  - BULB
    - Better regulation
    - Current monitor -> beam permit
- New kicker power supply
- Beam intensity doubled, but beam loss in water-bearing rock must not double
  - New 1 mil Ti multiwires - lower mass in beam